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NEW PERMIAN REPTILES: RHACHITOMOUS VERTEBRAE

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On the last day of field work by the University of Chicago Expedition to the Permian of Texas in the autumn of 1909, Mr. Lawrence Baker of the expedition discovered on Craddock's Ranch, about six miles from the town of Seymour, a remarkable deposit of fossil bones. All that could be done at the time was to collect a quantity of the loose bones from the surface. Work was begun upon the deposit by Mr. Paul Miller the present season, and, although the results obtained were not what had been hoped for and confidently expected, perhaps two hundred or more specimens were obtained. The bones were found almost invariably isolated, but in the most perfect preservation, for the most part entirely free from matrix; others were more or less covered by, or cemented together in, nodular concretions. The clay beds in which they were found, because of their usual barrenness, had never been thoroughly examined by previous collectors, and the bone deposit, though but a few hundred feet away from a well-traveled road, had been overlooked.

An incomplete examination of the material obtained shows a great variety of genera, not the less interesting because of their association. It includes various shark spines; a small quantity of *Diplocaulus* remains; at least three other forms of unidentified

amphibians represented by limb bones and parts of skulls; and certain large intercentra which agree well with those of *Trimerorhachis*. At least one of these amphibians has a wide dermal armor of a new kind, probably belonging with one or the other of the humeri from this deposit figured by me in my recent paper on *Cacops*.[1] Other limb bones and such parts of the carapace as have been recovered I will figure as soon as opportunity permits.

Among the reptile remains there are representatives of at least seven genera, including three distinct species of *Dimetrodon*, one of them the largest vertebrate hitherto recorded from the Permian of Texas; numerous vertebrae and teeth of *Diadectes;* limb bones which agree well with Case's figures of *Clepsydrops natalis*, and with limb bones in the collection obtained elsewhere; femora and humeri, as well as other limb bones of at least two distinct genera which I cannot yet identify, some of which are, with scarcely a doubt, new; vertebrae, parts of a humerus and femur which I refer to *Desmospondylus;* and the genus *Araeoscelis* herein described. Rather interesting is the fact that, so far, no certain evidence is forthcoming of the Pariotichidae, the curious acrodont *Pantylus*, Poliosauridae, Eryopidae, or Cricotidae. A few vertebrae having short spines with a pair of lateral tubercles suggest the probability of *Naosaurus*, and it is possible that some of the girdles and limb bones may be of this genus. Altogether I recognize in the deposit evidences of fourteen or fifteen genera and seventeen species.

Among the material recovered from this deposit is a temnospondylous coracoscapula, in which the three elements are separate. The suture between the coracoid and scapula is quite as in the pelycosaurian girdle, passing directly forward through the preglenoid articular facet and above the supracoracoid foramen. The metacoracoid is small, a mere vestige in fact. The evidence furnished, not only by the temnospondyls but by the almost identical structure of the coracoscapula of the contemporary reptiles, is, it seems to me, conclusive that there is no such bone as the procoracoid, that the coracoid of all modern reptiles is homologous with the anterior element, the so-called procoracoid, and not with the posterior one, which has disappeared, or remains as the merest

[1] *Bull. Geol. Soc. Amer.*, XXI (1910), 249, Pl. XV, Figs. 4, 5.

fused vestige. For this reason I abandon the term procoracoid and adopt the terms metacoracoid and coracoid, or epicoracoid if one desires a distinctive name for the anterior element, after Howes and Lydekker, the former of whom reached the same conclusion from the study of the mammals.

Araeoscelidae, family new.

Araeoscelis gracilis, genus and species new.

This species is represented by numerous remains found associated in a space of a few square feet, including various limb bones and vertebrae found free in the clay, and three or four more or less complete skeletons imbedded in clay nodules—in a more or less disturbed condition. There are parts or wholes of four or five skulls among them, but unfortunately their delicacy is such that they are more or less distorted and only by a careful preparation with needle and lens can one hope to determine their characters. This much however may be said: The teeth are placed closely together and are of uniform size, obtusely pointed as seen from the side, with their bases rather wider than long; there is but a single row. There is a row of slender conical teeth on the palate. The orbits are large, and almost certainly there is a single large temporal vacuity. The skull is lizard-like in shape, in the smallest about 30 millimeters in length; in the largest about 50.

The vertebrae, of which there are numerous free examples in the collection, in addition to several more or less complete series, in the nodules, are remarkable for their slenderness and delicacy. The dorsal vertebrae (Figs. 13, 17) are elongate, narrowly keeled below, with a rudimentary spine in front; there is a short diapophysis just back of the front zygapophyses; and intercentra are present.

The ribs, of which there are numerous free representatives, are rather stout and single headed—a unique character if it is representative of the whole dorsal series. The caudal vertebrae (Plate I, Figs. 11, 12) are remarkable for their great elongation and slenderness, having a slender carina on the under side, and a small parapophysial facet on each side in front, for the attachment of ribs, another remarkable character. The pectoral and pelvic girdles are present in at least two specimens, but are scarcely visible in

the hard matrix, save that the clavicles and interclavicle are seen to be very slender.

It is in the limb bones that the chief distinctive characters of the genus are found, characters hitherto unknown among American Permian vertebrates, characters which indicate a quick-running terrestrial, or, more probably, climbing reptile. The humerus (Plate I, Figs. 4, 5) is very slender and delicate, with slightly expanded extremities and a somewhat curved shaft. The articular head is elongate oval in shape, imperfectly separated from the lateral process, which is situated much closer to the head than in any other Permian reptile known to me. The bicipital fossa is rather deep, and there is no distinct median process. The distal extremity is very thin and flat, and only moderately expanded on the ulnar side. The entepicondylar foramen is small, and is situated some distance above the lower end. On the radial side there is a small ectepicondylar foramen situated close to the distal margin, formed by a bridge over the end of the ectepicondylar groove; it is very like the foramen of *Iguana*. The capitellum for the radius is perfectly formed, as is also the trochlear surface for the ulna; both of them are very small for the slender epipodial bones. There is no more characteristic bone in the early reptiles than the humerus. "Ein geübtes Auge und ein durch Nachdenken gescharfter Blick findet in dem Humerus der Reptilien zahlreiche Momente, welche von mehr oder minder systematischer Bedeutung sind, welche aber, was noch wichtiger ist, zugleich ein Stück Genealogie ablesen lassen."[1] Among Permian reptiles I know of none other in which the length exceeds the greatest width more than two and a half times; in the present species the length is three and three-fourths times the greatest width, a difference not often exceeded among reptiles. And, even in those reptiles with a higher index, I know of none in which the shaft is proportionally more slender. This extreme slenderness, together with the smoothness of the bones, the absence of muscular rugosities, and the perfectly formed articular surfaces, points, I think, toward climbing habits, or at least toward purely terrestrial habits. For comparison I have given in the plate (Figs. 1, 2) the most slender humerus of the American

[1] Fürbringer, *Jenaischer Zeitschr. für Naturwissensch.*, XXXIV (1900), 555.

Permian that I knew hitherto, and I know no less than twenty different forms of Permian humeri. It is that of one of the smallest of known Permian reptiles, *Pleuristion* Case, belonging in the Pariotichidae. As will be seen, however, the expansion of the extremities is great, though the shaft is slender. In the same plate (Fig. 3) I give a figure of the humerus of *Sphenodon punctatus* for comparison. It will be observed how clumsy the bone is in comparison with that of *Araeoscelis*. For comparison's sake I figure the humeri of *Pleuristion* and *Sphenodon* twice natural size. The concurrence of an entepicondylar foramen and an ectepicondylar groove is found in the pelycosaurs, but the groove is never converted into a foramen. That the presence of a foramen in the present genus is of great phylogenetic significance I do not believe.

The same slenderness is characteristic of the femur and leg bones. In Plate I, Figs. 7 and 8, I give, enlarged one-half for the sake of comparison, illustrations of a femur of one of the numerous young specimens, specimens lacking the articular ossifications and muscular markings. That it belongs with the same species as does the larger bone shown natural size in Figs. 9 and 10 there can be no doubt, notwithstanding the apparent differences, since about a dozen femora of various sizes are present in the collection, as also many humeri of various degrees of ossification and size. In the side view will be seen the remarkable sigmoid curvature so characteristic of the bone. The adult bone shows sharply defined the articular surfaces for epipodial bones, and, proximally, the well-developed, rounded head and trochanter. The shaft is proportionally somewhat stouter than is that of the juvenile bone, and the extremities are more sharply expanded. The tibia and fibula are extremely slender, very nearly or quite the full length of the femora; the tibia has a well-developed and protuberant cnemial process, better developed than I have observed in any other Permian vertebrate. The metapodials are likewise very slender, those of the hind feet apparently more so than those of the front feet, as are also their phalanges. I hope to be able in a later communication to give the complete or nearly complete structure of the hind extremities at least. The claws are slender and

sharp, the phalanges well formed. All the bones of the skeleton are very hollow.

Upon the whole the present animal must be a remarkably long-legged and long-tailed reptile, probably eighteen inches or more in length.

There are several small reptiles from the American Permian of which we yet have no published knowledge of the extremities, such as *Isodectes*, *Helodectes*, and *Pariotichus* sens. str., the most of which are at once eliminated from comparison with the present genus by reason of their roofed-over skulls. *Tomicosaurus* Case, described from a fragment of a mandible and several arches of vertebra differs in being a larger animal, and in the character of the teeth, as described by Case. The front teeth neither in the upper nor lower jaws are elongated or incisiform. Nothing is shown in the figures of the diapophyses. The two small vertebrae upon which the genus and species *Embolophorus fritillus* Cope were founded differ materially from those of the present genus. As to its ordinal position, nothing definite can be said of *Araeoscelis* till the skulls have been cleaned and studied, and possibly not even then, save of the presence of a temporal vacuity. To locate such a genus in the same group with *Dimetrodon* or *Naosaurus* seems a bit absurd.

Casea broilii, genus and species new.

The material upon which the present genus and species are based comprises, probably, several complete skeletons found associated with skeletons of *Varanosaurus* and *Cacops*.[1] The complete working out of the material may require a year or more. The characters are, hence, drawn from those parts of one skeleton now prepared, comprising the larger part of a tail, the sacrum, two lumbar vertebrae, pelvis, and the complete hind legs. I take pleasure in naming the genus and species after Doctors Case and Broili, who have extended our knowledge of the American Permian fauna so materially.

The chief character wherein the present genus differs from all hitherto known Permian reptiles of America is found in the ilium,

[1] *Bull. Geol. Soc. Amer.*, XXI (1910), 249–85, Pls. VI–XVI.

which has a broad anterior projection, and only a slight posterior one (Fig. 1, A) suggesting affinities with the African Therapsida.

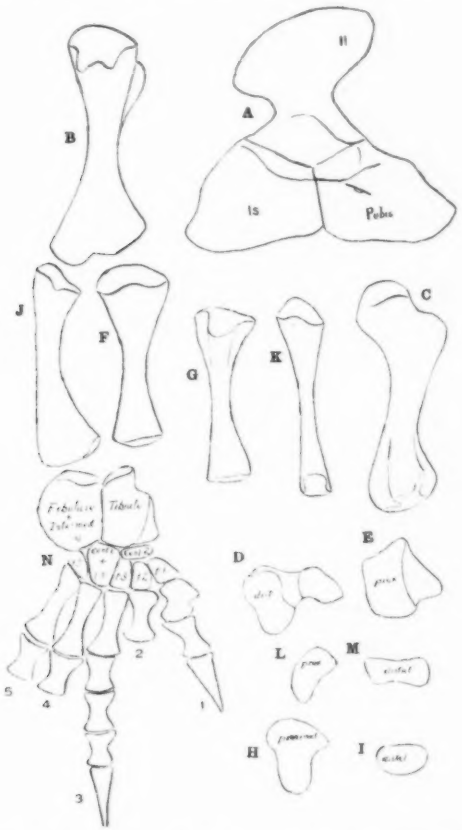


FIG. 1.—*Casea broilii* Will. A, right innominate, from without; B, right femur, dorsal; C, right femur, inner side; D, the same, distal end; E, the same, proximal end; F, right tibia, ventral; G, the same, dorsal; H, the same, proximal; I, the same, distal; J, right fibula, dorsal; K, the same, inner; L, the same, proximal; M, the same, distal; N, right foot, dorsal. All figures one-half natural size.

The pubes and ischia also differ markedly from both the clepsydropid and poliosaurid types in the absence of the platelike

projection anteriorly, agreeing rather better with the pariotichid type. The symphysis is continuous or nearly so throughout, without a median puboischiadic interval. The sacrum has three pairs of large sacral ribs, agreeing in this respect with the Clepsydropidae, and very different from the Poliosauridae, which have but two pairs. The spines of the vertebrae of the basal caudal, sacral, and lumbar regions at least are low cylindrical, with a nodular extremity, quite unlike the elongated forms of the Clepsydropidae and the moderately elongated and flattened spines of the Poliosauridae. Evidently the short co-ossified ribs of the lumbar regions are united to both arch and sacrum, and the ribs more anteriorly have double heads. None of the spines are elongated, as is indicated by numerous isolated vertebrae found in the wash. The femur (Fig. 1, B, C, D, E), tibia (Fig. 1, F, G, H, I), and fibula (Fig. 1, J, K, L, M) are sufficiently well shown in the figures. They are all much heavier and shorter than the corresponding bones of *Varanosaurus*. Of the feet (Fig. 1, N) I figure only those bones which were found in natural articulation; the remainder were detached in the feet studied. The phalangeal formula, as in *Varanosaurus* and *Dimetrodon*, is 2, 3, 4, 5, 4. The foot differs materially from that of *Varanosaurus* and its allies in the large size of the fifth digit. The second centrale is well ossified, whereas in *Varanosaurus* it was small in both front and hind feet and remained cartilaginous throughout life. It is very evident also that the foot was placed at a greater angle with the leg in walking. That the animal was of the crawling, lizard-like habit and form is undoubted. The present genus in all probability belongs to the order Pelycosauria as at present bounded. Nevertheless the marked differences in the pelvis may indicate corresponding differences in the skull. Furthermore I protest against the union of the Poliosauridae, or *Varanosaurus* at least, in the same group with *Dimetrodon* or *Naosaurus*. The structure of the skull, with no lower temporal arcade, aside from other characters of the skeleton sufficiently justifies a subordinal position.

Trispondylus texensis, genus and species new.

A new genus and species of reptile is represented in the Chicago collection by a considerable part of a skeleton collected by Mr.

Paul Miller on Craddock's Ranch intimately associated with the remains of *Trematops* described by myself. The parts recovered consist of a nearly complete humerus, radius, ulna, numerous carpal and digital bones, a pelvis lacking part of the ischia and pubis, and a more or less connected series of nineteen vertebrae. The

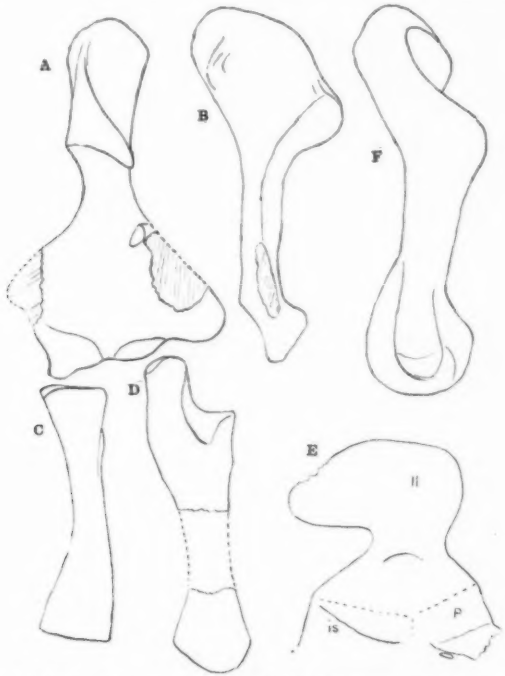


FIG. 2.—*Trispondylus texensis* Will. A, right humerus, ventral; B, the same, outer; C, right radius, dorsal; D, right ulna, dorsal; E, right ilium, outer; F, left femur, inner side. All figures one-half natural size.

vertebrae are in five series, three dorsal of three each, eight in another comprising two lumbar, three sacral, and three caudal, and two additional connected caudals. None of the spines of the vertebrae are preserved complete, but they are all evidently short. The centra are of nearly uniform length, a little shortened in the lumbar region, obtusely keeled below, or rather with the sides "pinched in." The ribs are double headed, the diapophyses anteri-

orly unusually long. Three of the basal caudals have intercentra, the first chevron appearing between the third and fourth caudals. The three pairs of sacral ribs are turned broadly down at their extremities, the expansion of the first pair nearly equal to the combined extent of the second and third pairs. The ilium (Fig. 2, E) has the ordinary form, turned broadly backward, and is wholly without an anterior projection. The humerus (Fig. 2, A, B) is massive and broad, with the distal extremity greatly expanded; the radius and ulna (Fig. 2, C, D) are likewise stout bones. The front feet show the usual structure, so far as the preserved remains enable one to decide; the intermedium is large, the second centrale is ossified, and the pisiform articulates with the distal end of the ulna. The femur (Fig. 2, F) is likewise a stout bone, especially characterized by the low position of the trochanter.

The genus is removed from the Poliosauridae by the possession of three sacral vertebrae; from the Clepsydropidae by the possession of short dorsal spines, and the different structure of the propodials, as will be seen by comparison of the same parts of *Clepsydrops* and *Dimetrodon*.

THE DEVELOPMENT OF HOLOSPONDYLOUS VERTEBRAE

In a recent paper[1] I discussed the views at present held as to the morphological significance of the rhachitomous pleurocentra and hypocentra in the evolution of vertebrae of the higher forms. The majority of paleontologists believe that the rhachitomous type of vertebra is a primitive one, though there are some, of whom Jaekel is one,[2] who deny it. The extraordinary resemblances in nearly all parts of the skeleton between the more specialized temnospondyls and the more generalized reptiles are almost a demonstration of genetic affinity. That we have in any known Permian forms the actual connecting links between the Amphibia and Reptilia is more than doubtful; it is more than probable that annectant forms must be sought for in older rocks, probably those of the lower part of the Pennsylvanian or Upper Carboniferous.

[1] *Bull. Geol. Soc. Amer.*, XXI (1910), 265.

[2] *Deutsch. geolog. Gesellsch.*, LVI (1904), 118; *Zoologisch. Anzeiger*, XXXIV (1909), 200.

If then we assume that the holospondylous vertebra has been evolved from the rhachitomous, it is a matter of much interest to determine how the evolution has occurred. The view which has obtained general acceptance, among American paleontologists at least, is that of Cope, so vigorously defended by Baur,[1] namely, that the pleurocentra have progressively developed to form the centrum of the amniote vertebra, the hypocentrum degenerating into the vestige usually called the intercentrum; while, as proposed by Cope and tentatively accepted by Baur, in the modern amphibians it has been the hypocentrum which has developed into the centrum, the pleurocentra disappearing. The theory more generally accepted by European writers is that the pleurocentra and hypocentrum have fused to form the centrum of all the higher vertebrates, the small elements called the intercentra representing, according to Gadow and others, the hypocentra pleuralia, which have been rarely found in the tail of certain temnospondyls. Or, in the words of Broili:

> Bei den Rhachitomen das Hypozentrum den ventralen Halbring und das Paar der Pleurozentren den dorsalen Halbring des Wirbelkörpers repräsentirt; anderseits folgt daraus, dass weder das Hypozentrum noch die Pleurozentren allein dem eigentlichen Wirbelkörper der Amnioten homolog sind, sondern das beide zusammen Hypozentrum plus Pleurozentren desselben entsprechen.[2]

A study of the material in the University of Chicago collections has convinced me of the general correctness of Cope's contentions and the incorrectness of the opposing views.

It is well known that in the older reptiles the odontoid of the atlas is a larger bone than in modern reptiles or higher vertebrates, and also that there is in the oldest forms invariably a large intercalating intercentrum between the odontoid and the body of the axis below, a bone that is small or wanting in modern reptiles, as also the older Crocodilia. In *Dimetrodon*, as will be seen in the accompanying figure (Fig. 3), the odontoid functions as the real centrum of the atlas, reaching quite to the ventral side between the atlantal and axial hypocentra. It has a deep conical cavity

[1] "Everybody is convinced that the pleurocentra of the Rhachitomi represent the centra of the higher vertebrates; and that the intercentra are homologous to the intercentra of the Sphenodontidae," etc.—*Amer. Nat.* (1897), 975.

[2] *Monatschr. d. deutschen geologischen Gesellschaft*, LX (1908), 240.

in its posterior end, that in apposition with the body of the axis, a cavity which extends through the bone as the notochordal canal. Not only does this cavity extend through this bone but its orifice, in *Varanosaurus* at least, is in apposition with a similar cavity in the occipital condyle, conclusively proving the nature of the basioccipital. Between the odontoid and the axis, below, there is a large, massive intercentrum, even larger than the atlantal hypocentrum. This latter intercentrum gives support only in part to the neuropophyses of the atlas, which rest chiefly on the odontoid.

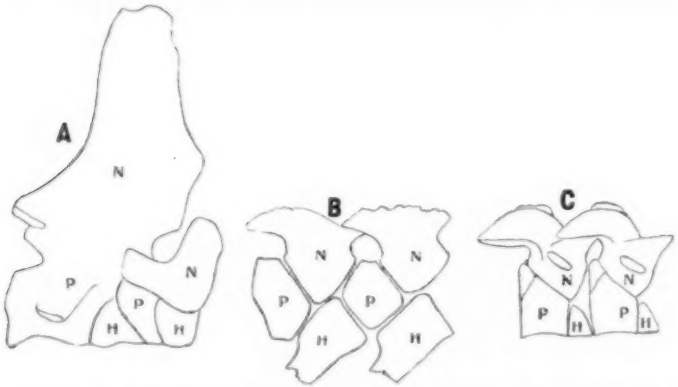


FIG. 3.—A, Atlas and axis of *Dimetrodon incisivus* Cope; B, caudal vertebrae of undetermined amphibian; C, vertebrae of *Desmospondylus anomalus* Will.; N, neurocentra; H, hypocentra; P, pleurocentra.

There can be no question that the odontoid is the combined pleurocentra of the atlantal vertebra, which has so far retained its primitive character that it gives chief support to the atlantal neuropophyses. Yet more conspicuously holospondylous in character is the atlas of *Poecilospondylus* Case, in which the dorsal arch appears to rest wholly upon the odontoid, and articulates in the usual way with the axis.[1] In *Eryops*, *Cacops*, and doubtless all other rhachitomous genera the vertebrae of the trunk have a perforating canal for the notochord formed by the junction of the pleurocentra in the middle above the hypocentrum, the three bones forming the canal; and it is chiefly because of this fact that Broili

[1] *Bulletin Amer. Mus. Nat. Hist.* (1910).

believes that the holospondylous centrum is formed by the fusion of the three bones. Under this theory, the intercentra, using the term as originally applied by Cope, must be morphologically different elements from the hypocentra. If such be really the case, it seems probable that all the known temnospondyl amphibians must be excluded from ancestral relationships with the reptiles, since none of them is known to possess additional elements in the trunk region. Aside from the improbability that the hypocentra pleuralia, known only in the tail of one or two temnospondyls I believe, have developed into so large a bone as is the axial intercentrum of *Dimetrodon*, the relations and structure of the axial and atlantal bones in the old reptiles furnish certain proof, it seems to me, that the odontoid is composed exclusively of the pleurocentra, though perforated by the notochordal canal; and Broili's argument falls to the ground.

Yet more conclusive evidence—it seems to me irrefutable—is furnished by two caudal vertebrae (Fig. 3, B) of an unidentified amphibian from the Texas Permian. The specimen was found by Mr. Paul Miller in the autumn of 1908 on the Little Wichita, unassociated with other bones. The size of the vertebrae rather precludes the probability of their belonging with *Eryops*, though possibly coming from near the extremity of the tail. However that may be, I doubt not that a similar structure will be found to be characteristic of *Eryops*, since by the aid of this specimen I determine a like structure in the tail of *Trematops*, as was indeed indicated by me in my paper descriptive of that genus.[1] Very probably the specimen pertains to a species of *Trimerorhachis*. The two vertebrae composing the specimen are closely associated, without distortion, and are uninjured, save for the loss of the greater part of the chevrons, and a part of the arch of the proximal vertebra. The two arches (NN), it will be seen in the figure, are wedged in between their adjacent pleurocentra (PP), resting in part upon the hypocentra (HH). The first pleurocentrum does not quite separate the two adjacent hypocentra below, which nearly touch at their extremities. The second pleurocentrum, however, is almost disklike, narrowed above and below, but separating by a

[1] *Journal of Geology*, XVII (1909), 647, Figs. 5, 16.

considerable interval both the arches and the hypocentra of the adjacent vertebrae. This pleurocentrum forms a complete ring, without traces of division, conically hollowed in its visible end and perforated by the notochordal canal. Its neurocentrum is much more closely and extensively combined with it than with the preceding pleurocentrum. In a few words, this vertebra is still typically rhachitomous, save that its fused pleurocentra form a disk separating the adjacent vertebrae, which is perforated like any holospondylous centrum by the notochord. The most imaginative eye will not see in this vertebra fused pleurocentra and hypocentrum with some other element taking the place of the hypocentrum, since the preceding apparently fused pleurocentra are not very different from the ordinary form. Doubtless the pleurocentra preceding these were progressively smaller, and those following progressively larger. To follow Jaekel's arguments to their extreme would necessitate the fusion of hypocentra and pleurocentra throughout, and the sudden introduction of an entirely different element in the chevrons to mimic the hypocentra, of all of which there is not the ghost of evidence!

The next stage in the evolution of the ordinary holospondylous vertebra may be seen in the reptile *Desmospondylus*, as recently described and figured by me,[1] an outline copy of two of the vertebrae of which I reproduce (Fig. 3, C). In his specimen it will be seen that the fused pleurocentra (PP) have increased in size, while the hypocentra (HH) have decreased, though still much larger relatively than in any other known reptile. The arch (N) rests in the same way upon the two adjacent pleurocentra, though functionally upon the posterior one, its own, and its lower extremity in front nearly touches the upper extremity of the hypocentrum.

From these three specimens it is not at all difficult, it seems to me, to understand clearly the way in which the different types of vertebrae have arisen. By the fusion of the neurocentrum with its respective hypocentrum, the embolomerous vertebra has arisen; by its sutural union with its respective pleurocentra the reptilian vertebra is produced; by the union of all three, I believe, the holospondylous amphibian vertebra has been evolved. It would

[1] *Bull. Geol. Soc. Amer.*, XXI (1910), 280.

require but little change in the size of the different parts to develop the second vertebra shown in B into one of those shown in C. In any event I think the specimens show conclusively that the hypocentra or intercentra are not the hypocentra pleuralia, as Gadow believes, nor the pleurocentra the fused pleurocentra and hypocentra, as Jaekel, Broili, and others believe.

Cope suggested that the pleurocentra were eliminated in the evolution of the holospondylous amphibian vertebra, but it seems more reasonable to me that there has been a fusion of all three elements in the Branchiosauria, Lepospondyli, and modern amphibians, from the fact that none of these amphibians are known to possess any vestiges as separate elements.

If this theory be true, that is the union of the hypocentra with some or all the other elements of the vertebrae in the amphibia, and their final loss, save as simple intercentra and chevrons in the amniota, it would offer of course the best class distinction between holospondylous amphibians and reptiles. In any event the structural differences seem too radical to unite forms with free chevrons articulating intercentrally with those having no free intercentra and the chevrons exogenous processes from the body of the vertebra. Nevertheless that is what is done in the order Microsauria. Baur some years ago reached the conclusion that *Hylonomus* and *Petrobates* were undoubted reptiles,[1] and his views were accepted by Fürbringer and others. A study of the specimen described by Cope and doubtfully referred by him to the species *Tuditanus punctulatus* Cope under the name *Isodectes* (*Eosauravus copei* Will., *Isodectes punctulatus* Moodie, nec Cope) convinces me that the genus is allied to *Hylonomus*, and consequently is a true microsaur, since *Hylonomus* Dawson is the type, with *Dendrerpeton* Owen, and *Hylerpeton* Owen, of the order Microsauria, as proposed by Dawson in 1863 (Airbreathers of the Coal Period). Whether *Hylonomus*, *Petrobates*, *Eosauravus*, and *Sauravus* Thevenin are true reptiles, even though having free chevrons, will not be positively determined until the structure of the skull has been made out. Whatever is the final disposition of them, they must be excluded from the Amphibia, and doubtless the ordinal name Microsauria will remain

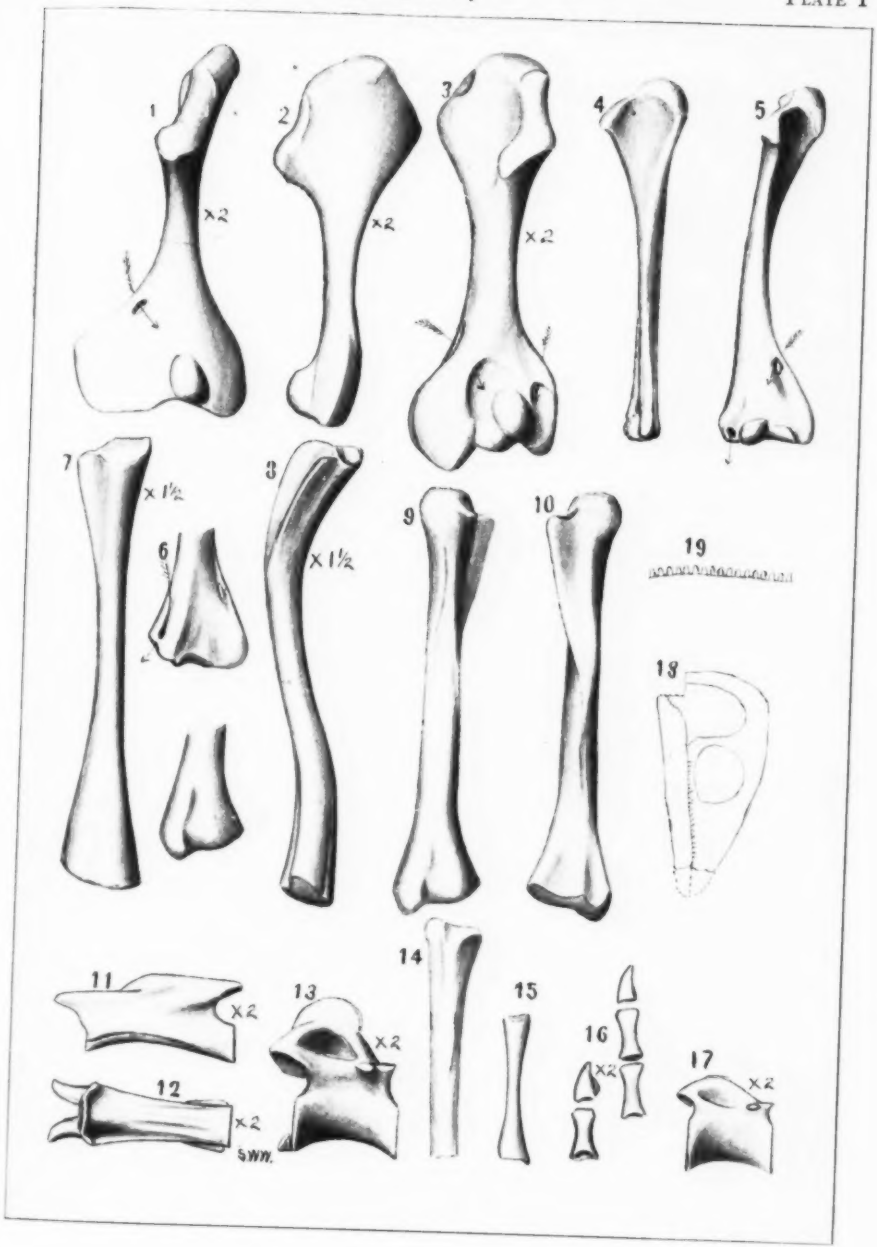
[1] *Anatomischer Anzeiger*, XIV.

valid for them. With the elimination of these genera, and perhaps others, from the Amphibia there remain a number of others hitherto classed under the Microsauria, of which *Urocordylus*, *Crossotelos*, and perhaps *Diplocaulus* are typical, that are genuine stegocephalian amphibians, which can no more be classed with the Reptilia than a salamander can. They have exogenous chevrons, and double-headed ribs attached to body and arch, true amphibian characters, the former utterly unknown among reptiles, save apparently in such rare cases as *Clidastes* among the mosasaurs, purely the result of a secondary anchylosis. There have been plenty of terms proposed to include them, such as Nectridea Miall, Lepospondyli Zittel, Diplocaulia Moodie, Holospondyli Jaekel. For myself I prefer the term Lepospondyli. Jaekel's class Microsauria is untenable.

Whatever may be the final disposition of *Lysorophus*, which I have referred to the order Urodela or Caudata, there can be hardly a question of its urodelan affinities. It has nothing to do with the Gymnophiona. The abundant material in the University collections demonstrates the presence of small limbs in numerous specimens. Amphiuma-like in form it had Amphiuma-like habits and limbs. I may also add that the supposed proatlas described both by myself and Case is merely the arch of the so-called atlas.

EXPLANATION OF PLATE

FIG. 1, *Pleuristion brachycoelus* Case, left humerus, ventral side; FIG. 2, the same, outer side; FIG. 3, *Sphenodon punctatus*, left humerus, ventral side; FIG. 4, *Araeoscelis* gracilis Will., right humerus, inner side; FIG. 5, the same, ventral side; FIG. 6, the same, distal end, dorsal side; FIG. 7, *A. gracilis*, left femur of young individual, dorsal side; FIG. 8, the same, inner side; FIG. 9, *A. gracilis*, adult femur, dorsal side; FIG. 10, the same, ventral side; FIG. 11, *A. gracilis*, caudal vertebra, side view; FIG. 12, the same, from below; FIG. 13, *A. gracilis*, dorsal vertebra, from side; FIG. 14, *A. gracilis*, upper part of tibia; FIG. 15, *A. gracilis*, metapodial; FIG. 16, *A. gracilis*, phalanges in position as found; FIG. 17, *A. gracilis*, dorsal vertebra; FIG. 18, *A. gracilis*, sketch of skull; FIG. 19, *A. gracilis*, mandibular teeth. All figures natural size, save where indicated.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THE PHYSIOGRAPHY OF THE BISHOP CONGLOMERATE, SOUTHWESTERN WYOMING[1]

JOHN LYON RICH
Cornell University, Ithaca, N.Y.

Introduction.—The purpose of this paper is the description of a series of peculiar, gravel-capped plateaus in the southwestern part of Wyoming, and an attempt to decipher, in so far as the evidence will permit, the physiographic history of the region both before and after the deposition of the gravels. It will be shown that a study of the physiography leads to some interesting and suggestive conclusions as to past changes in the geography of the region described, which on the whole agree remarkably well in broader features with certain conclusions which have been reached from other lines of approach.

Geologists are recently beginning to recognize more clearly than ever before the importance of climatic conditions in determining the nature of the geologic processes at any given time, and in determining the nature of the deposits formed as a result of these processes.[2] At the same time they are beginning to reason back from the character of a deposit to the causes which are responsible for its distinctive features; to the climatic and other conditions under which the deposit was made. It is one of the purposes of this paper to call particular attention to this line of study by attempting to show from physiographic evidences that there have been in comparatively recent geological times a series of marked climatic changes affecting the region under discussion.

[1] Published by permission of the Director of the U.S. Geological Survey. The writer is indebted to Dr. Alfred R. Schultz for information in regard to conditions on Little Mountain, for certain of the accompanying photographs, and for helpful discussions in field and office; also to Professor A. C. Gill for a reading and criticism of the manuscript.

[2] Joseph Barrell, "Climate and Terrestrial Deposits," *Jour. of Geol.*, XVI; Ellsworth Huntington, "The Glacial Period in Non-glaciated Regions," *Bull. Geol. Soc. Am.*, XVIII, 351–88; Chamberlin and Salisbury, *Text Book of Geology*, III, 305–7, 452–53.

The paper, aside from its descriptive part, is an inductive and deductive study carried out with the idea of reconstructing the past history of the region from the physiographic features still remaining.

There is in the southwestern part of Wyoming a belt of plateau country skirting along the northern base of the Uinta Mountains

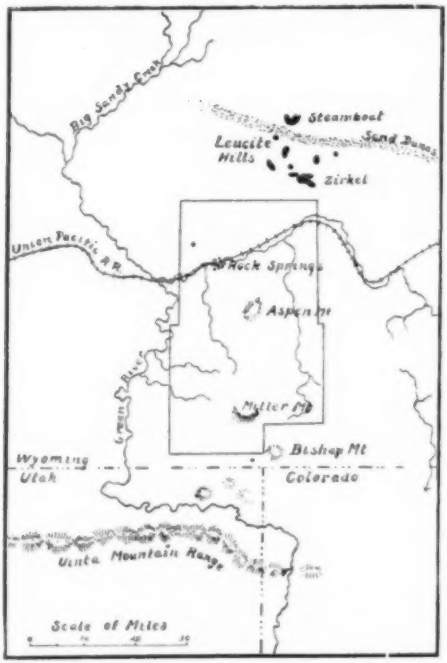

FIG. 1.—Sketch map of portions of Wyoming, Utah, and Colorado, showing the general location of the features described in this paper.

in an east-and-west direction parallel to the range. This has a general slope to the north away from the mountains. During the summer of 1908 a portion of the plateau lying north of the eastern end of the range and north and east of Green River was mapped in detail by a United States Geological Survey party. The conditions observed in that portion of the area form the basis of this paper. Fig. 1 is a sketch map of parts of southwestern

Wyoming, Utah, and Colorado which will indicate the general location of the region and its relation to the near-by important physiographic and geographic features. Fig. 2 is a more detailed map of a portion of the area outlined in Fig. 1 and shows all the various topographic, hydrographic, and cultural features referred to in the following discussion.

Referring now to the detailed map it will be noted that the entire area is drained by tributaries of Green River. Bitter Creek, one of the largest of these entering from the east, drains all but the extreme southern and western part. Red Creek takes the waters of the southern part directly south to Green River, and Sage Creek, flowing northwest, carries the drainage of the western part directly to the river.

The climate is semi-arid, with an average rainfall of from ten to fifteen inches per year. The topography is typically that of a semi-arid region of moderate relief; low areas, corresponding to belts of soft rock, are followed by steep scarps with dip slopes. Each zone of harder rocks is represented by a more or less pronounced scarp, depending on the resistance, thickness, and dip of the component layers. One of these scarps formed by a series of heavy-bedded sandstones is over 1,000 feet in height.

The plateau.—The most conspicuous feature of the topography within the area of the detailed map is a high, even-topped plateau lying at an elevation of from 1,000 to 1,500 feet above the bottoms of the major stream valleys. This is everywhere capped by a gravel-deposit partly consolidated at the base into a resistant conglomerate which, on account of its resistance to erosion, is responsible for the preservation of the plateau while the surrounding country was worn down. From its northern extremity at the northwestern base of Aspen Mountain the plateau extends southward for a distance of fourteen miles to Miller Mountain where it ends abruptly in a steep scarp facing southward to the basin of Red Creek. The plateau varies in width from less than a mile to eight or ten miles. The largest remnant extends southward from Aspen Mountain to Miller Mountain as indicated, but there is a long arm running northwest from Miller Mountain between the valleys of Sage and Little Bitter creeks for a distance

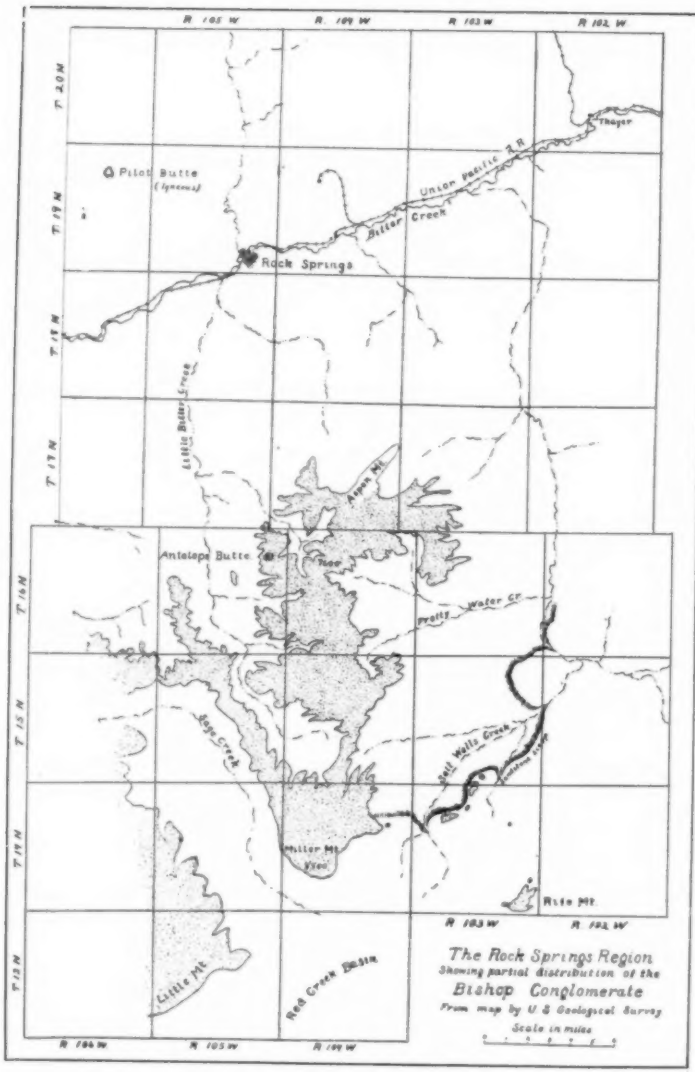

FIG. 2.—Map of the Rock Springs region

of fifteen miles or more, nearly to Green River. A similar plateau, known as Little Mountain (Quien Hornet Mountain of the Powell Survey), lies to the west and southwest of Miller Mountain, from which it is separated by the deep valley of Sage Creek. Rife Mountain, a flat-topped mesa about two miles long by one mile broad lying nine miles east of Miller Mountain, is a detached remnant of the same plateau lying at an accordant altitude and capped by similar gravels. Between this and Miller Mountain are five smaller isolated gravel-capped areas lying at accordant altitudes. Ten miles southeast of Miller Mountain is a good-sized remnant of the same gravel-capped plateau known as Bishop Mountain, or sometimes locally as Pine Mountain. It is from this plateau that the gravel-formation, the Bishop Conglomerate, receives its name.

Bishop Mountain is the type locality of Powell's "Bishop Mountain Conglomerate" as defined in his Uinta Mountain report. The shorter term, "Bishop Conglomerate,"[1] has however recently been adopted by the Board of Geologic Names, and is, therefore, used here in preference to Powell's name. The Bishop Conglomerate is the same as the "Wyoming Conglomerate" of this same region as described by King in his "Survey of the 40th Parallel."

The surface of the plateau is everywhere even and the isolated portions all lie at accordant altitudes. The surface as a whole strikes about 20° north of west and slopes to the north from the most southern exposure to the low area four miles south of Aspen Mountain. There is then a rise toward the north to the base of the mountain. A few elevations will give an idea of the slope of this surface. The highest part of Miller Mountain is, in round numbers, 8,500 feet; Rife Mountain, 8,400 feet; the low area south of Aspen, 7,600; and the plateau at the west base of Aspen, 7,900 feet. Bishop Mountain is considerably higher and the same is true of the southern part of Little Mountain. The slope of the gravel surface is so even, and the accordance in elevation of isolated remnants is so close, that one may stand on the top of one of them and, looking along the strike, see the trees on the top of the others,

[1] A. R. Schultz, "The Southern Part of the Rock Springs Coal Field, Sweetwater Co., Wyo.," *Bull. U.S.G.S. No. 381*, 112.

even when the distance is six or eight miles. No suggestion of the intervening valleys then appears. This close accordance indicates that all the gravel-capped areas once formed parts of the same even plateau-surface and have been separated only by subsequent erosion. The plateau is still in the process of active dissection. Adjacent parts are in many cases separated by valleys over 1,000 feet deep whose tributaries, by working their way back into the plateau by head-water erosion, are responsible for the very irregular ground-plan of the parts still remaining. Fig. 3 gives a good

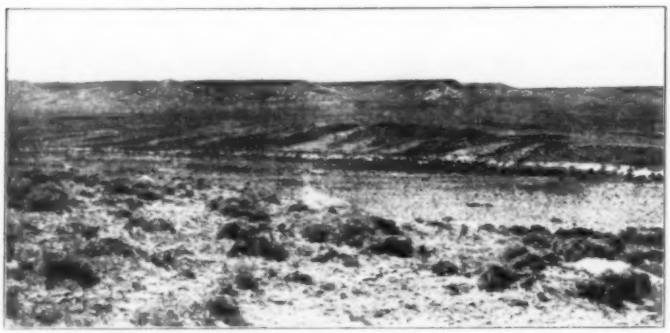

FIG. 3.—Miller Mountain plateau as seen from a distance of four and one-half miles, looking west from the banks of Salt Wells Creek. Note the even sky-line. The view shows the edge of the plateau for a distance of five miles without disclosing any visible irregularity. The conglomerate capping here averages between fifty and one hundred feet in thickness and is well cemented at the base. The top of the plateau is about 1,000 feet higher than the stream in the foreground. Between the stream and the base of the scarps the wash-apron described on a later page is fairly well shown.

idea of the sky-line of the plateau as seen from a distance of about four miles.

Character of the rock floor of the plateau.—As already stated, the entire plateau is capped by gravels which may be loose and unconsolidated in the upper part but are as a rule firmly cemented at the base. This conglomerate capping varies in thickness from eight to ten feet to as much as two hundred feet in different parts of the area. The rock-surface on which it lies is a very even, beveled rock floor which, though it may be slightly irregular in places, is on the whole remarkably smooth. In no part of the

area studied were noticeable irregularities in the surface evident in the exposed line of contact with the underlying rocks. In several places, but best along the eastern face of Little Mountain, this contact can be seen continuously for several miles, and in all that distance does not display any appreciable irregularity. The probable reason for this great regularity is that the underlying rocks are uniform in texture and quite soft. In localities where the underlying rocks are markedly unequal in hardness the contact is slightly irregular in detail, but still regular in general.

A large part of the gravel-capped plateau lies on the truncated

FIG. 4.—Unconformity of Bishop Conglomerate with underlying Cretaceous rocks southeast of Aspen Mountain. The dark horizontal bed at the top is the conglomerate. Note how evenly the base of this conglomerate truncates the dipping sandstones beneath. This is typical of conditions all along the edge of the plateau.

crest of the Rock Springs dome, a broad anticline of sedimentary rocks about ninety miles in length with the long axis running a little west of north through Aspen Mountain. This anticline has a total width of about forty miles. In the southern part of the area the plateau truncates the tilted rocks on the northern flank of the Uinta uplift. The beveling of the underlying rocks by the plateau-surface is very marked. In certain parts of the Rock Springs dome these underlying rocks dip in both directions from the crest, sometimes at an angle as high as 35°, yet the plateau-surface cuts evenly across them entirely irrespective of structure and almost irrespective of hardness (Fig. 4). Faults and folds in the underlying rocks have no expression in the plateau-surface.

The rock floor of this plateau is clearly a peneplained surface of very considerable extent and great regularity. We are not dealing in this case with an imaginary peneplain whose existence is deduced from the finding of hilltops at about the same level, but with one in which the original planed surface is still preserved over a broad area with its edges exposed and with an evenness the more striking on account of the folded condition of the underlying rocks.

Extent of the peneplain.—The portion of the area mapped in detail in the summer of 1908 in which remnants of the peneplain occur measures about twenty-seven miles from north to south and twenty-two miles from east to west. Including Bishop Mountain and the western part of Little Mountain which were not mapped in detail, but which are without doubt parts of the same peneplain, the dimensions just given will be increased by about ten miles in either direction. This makes an area of at least 1,200 square miles which we can definitely say was reduced to the condition of a peneplain of very slight relief.

There is good evidence that the peneplain had a much greater extent than that indicated by the area over which portions of the gravel-capped plateau still remain; for the lava-sheets of the Leucite Hills, which are scattered over a considerable area from fifteen to forty miles north of Aspen Mountain, lie on the beveled surfaces of the underlying sedimentary rocks. The lava-flows have preserved these beveled surfaces at their original elevations. These, in the case of the larger flows, are so nearly in accord, and so nearly agree with those of the gravel-capped plateaus to the south of Aspen Mountain, that it is reasonably safe to assume that the lavas were poured out on the surface of the same peneplain. The following figures will illustrate this relationship: Approximate elevation of the base of the gravels south of Aspen Mountain, 7,600 feet; base of Pilot Butte lava-flow, 7,900 feet; Zirkel Mesa, 7,600 feet; Steamboat Mountain, forty miles north of Aspen, 8,250 feet; and North Table Mountain, about 8,150 feet. All of these agree in that they, like the plateau to the south, stand from 800 to 1,200 feet above the level of the adjacent valleys. Several of the smaller lava-flows are at lower levels and do not agree closely with those mentioned above. A small flow three miles northwest

of Zirkel Mesa has an elevation of 7,900 feet, 300 feet higher than that of Zirkel. Most of the flows which are discordant are smaller and lower than the average and evidently were poured out after the principal period of extrusion on a surface somewhat reduced by erosion. The larger of the Leucite Hills lava-flows do not differ more among themselves as to elevation than do different parts of the Miller Mountain plateau itself.

Monadnocks.—Aspen Mountain which rises about 1,000 feet above the level of the plateau to the south is a ridge of resistant

FIG. 5.—Antelope Butte, a monadnock on the peneplain southwest of Aspen Mountain as seen from a distance of three and one-half miles. To the right in the middle distance is the head of a stream-valley which is working back into the plateau. This view gives a fair idea of the appearance of the surface of the plateau, though it is here somewhat less even than usual on account of proximity to the invading stream-valley. In the immediate foreground is a smaller monadnock similar to Antelope Butte. (Photo. by A. R. Schultz.)

quartzite formed by the impregnation with silica of a soft Cretaceous sandstone. On account of its superior hardness it stands as a monadnock on the peneplain. From the summit of the mountain there is on the north a steep drop to the lowlands of Bitter Creek, and to the south a gradual slope to the surface of the gravel plateau. At the time of planation Aspen was reduced to a moderate slope. The present steep slope on the north side of the mountain is the result of more recent erosion.

Six miles southwest of Aspen is a much smaller monadnock known as Antelope Butte which rises as a conical hill about 150 feet above the surface of the peneplain. Fig. 5, a view taken

from another small monadnock near the base of Aspen, shows well its character and relation to the surface of the gravels. This, like Aspen, is due to the silicification of a Cretaceous sandstone. Near by there are several other smaller masses of silicified sandstone projecting through the gravels which in this vicinity are comparatively thin, sometimes not more than ten or twelve feet in thickness.

Character and origin of the gravels.—The conglomeratic capping of the plateau is made up for the most part of gravel and sand of greatly varying texture. In the low area south of Aspen Mountain the pebbles are not as a rule more than from one-half to one inch in diameter, and the greater part of the material on the surface is a fine gravel or sandy loam derived from the disintegration of the conglomerate. As one goes south the material gradually becomes coarser till, at the southern end of Miller Mountain, bowlders varying from one to five feet or more in diameter are common. On the south slope of the mountain many large bowlders strew the surface to such an extent that passage with a horse is difficult. From the low area *northward* to Aspen Mountain the material also becomes coarser. In some of the deep gullies cut into this deposit one may find many bowlders like those shown in the photograph, Fig. 6. Diameters of four or five feet are not uncommon in this part of the deposit. The bowlders are subangular for the most part, like those shown in the photograph. They occur imbedded irregularly in finer gravels and sand.

The gravels are rudely stratified, but in ordinary exposures the stratification cannot be seen well. At first the deposit at the base of Aspen was thought to be of glacial origin on account of the large size of the bowlders, their subangular nature, and their occurrence scattered irregularly through the finer gravels. Later this idea was abandoned on account of the complete absence of striations on any of the bowlders, the lack of any signs of glacial action on the bed-rock underneath, and finally on account of the local nature of any possible supply ground. Aspen Mountain from which the material came is too small to have supported glaciers under any circumstances.

South of the low area the gravels consist largely of red and

white quartzites with occasional specimens of gneiss, schist, diabase, and limestone. There can be no doubt as to their origin in the Uinta Mountains to the south where similar rocks are found.

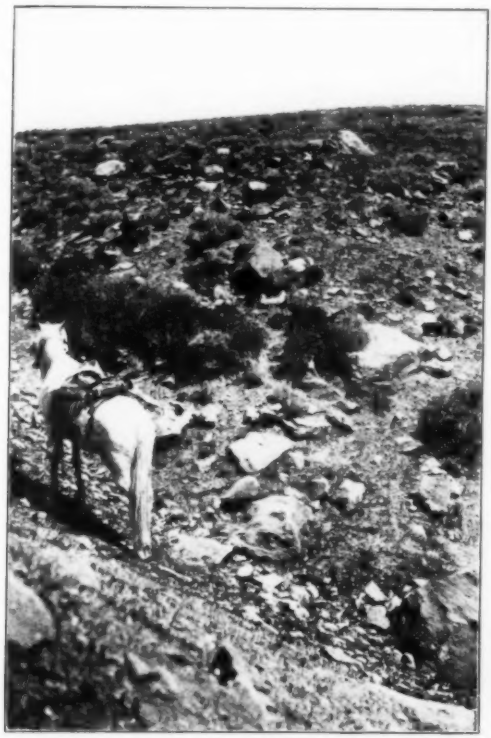

FIG. 6.—Bowlders exposed in a stream-gulley in the Bishop Conglomerate on the southeast flank of Aspen Mountain, well down on the plateau. This is a typical example of the coarser débris which has accumulated round the base of the mountain. It is of local origin, entirely distinct from the Uinta gravels to the south.

This origin is also amply indicated by the fact that the material becomes coarser toward the mountains. North of the low area, round the base of Aspen, the gravel is of local nature, derived from the sandstones and quartzites of the mountain. The surface here

slopes to the south in a direction opposite to that of the portion covered by the Uinta gravels.

The low area referred to is evidently fundamentally of a constructional nature lying at the junction of two fans, the one from the Uinta Mountains, the other from Aspen. Where these fans meet there is a distinct interfingering of the two kinds of gravel. In riding along in an east-and-west direction one is first on Uinta gravels, then on those from Aspen. Areas of one extend out into areas of the other. The vertical interlapping of the two was nowhere seen, though it undoubtedly exists. The whole relation of the two indicates that they were spread out at the same time the one from the Uintas, the other from Aspen Mountain.

INTERPRETATION

Planation.—From the relations just described it is evident that the Rock Springs region has been subjected to a long period of planation during which the surface of the land was reduced to the condition of a peneplain. The rocks were worn down until differences in structure produced no corresponding effect in the topography of the plain. In a few exceptional cases, like those of Aspen Mountain and Antelope Butte, hard rocks remained above the plain as monadnocks. That the plain was of considerable extent is shown by the fact that it covered not only the area south of Rock Springs as far as the Uinta Mountains, but also, as is indicated by the relation of the lava-flows of the Leucite Hills, all the area between the Uintas and the Wind River Mountains 200 miles to the north. Its limits are unknown.

Present differences in elevations of portions of the peneplained surface still remaining indicate that the whole region was reduced to the condition of a gently undulating plain of advanced old age with a relief of 700 to 800 feet in distances of 25 or 30 miles. This conception corresponds well with the observed great regularity of the plain surface in details and its broad irregularity when distances of 25 or 30 miles are considered.

As to the time of planation it is not possible with the information at hand to make any definite statement further than that it was later than the Green River Eocene. There can be no question

of this for along the eastern face of Little Mountain the peneplain truncates rocks of this age. From long-distance observations west of Green River it is thought that the planed surface will be found to truncate rocks of the Bridger formation along the southern rim of the Bridger basin. Gravel-covered, planed surfaces which may have originated at the same time as those of the Rock Springs region are reported by Woodruff[1] from the Wind River basin of Wyoming. The evidence there indicates that the planation was not completed until after the deposition of the White River Oligocene. The fossils in the gravels do not definitely determine the age, but the beds lie above various formations from Colorado up through and including Mesaverde, Cretaceous, and Wind River Eocene, younger than Fort Union. They were not seen in contact with White River beds, but deformations which moved the Wind River beds as well as the White River Oligocene, overlying, occurred previous to the deposition of these gravels, hence the inference that they are younger than White River. If these planed surfaces in the Wind River basin are the result of the same period of planation as those of the Rock Springs region, then the date of this is established with little question as later than White River Oligocene.

In the absence of more definite evidence from the area under discussion we can only assert that the planation took place in the late Tertiary, and that it was doubtless in late Tertiary time that the culmination of the base-leveling process was reached. Further observations in other regions or more extended observations in this region may later make it possible to assign a more definite date for the planation.

For the present discussion we will assume that planation was in progress during the latter part of the Tertiary, and that it ceased with the beginning of the crustal movements which occurred between the Miocene and the Pliocene; the reader meanwhile bearing in mind that this date is merely provisional pending the discovery of more exact data.

Climatic conditions at the time of planation.—Planation over

[1] E. G. Woodruff, unpublished data. See U.S. Geological Survey bulletin on the "Coal Beds of the Wind River Basin, Wyoming," soon to be published.

large areas may be accomplished by any one of three agencies: marine planation, subaërial denudation under conditions of moist climate, or denudation under arid conditions by wind scour. In the case at hand the first of these, marine planation, is thrown out of the question by the broad irregularities of the peneplain and its gently undulating nature, as well as by the improbability of such planation having occurred so far inland in late Tertiary times.

The second explanation, normal peneplanation under a moist climate, accords well with the facts. We find a smooth, yet gently undulating surface with differences in relief amounting to 700 or 800 feet at points twenty-five miles or more apart. This indicates slopes of from ten to thirty feet per mile. These conditions are what should be expected if the peneplain is the result of normal denudation under moist conditions.

In the third place there is the possibility of planation under arid conditions by wind scour. This agency in an arid climate is worthy of serious consideration, for, under favorable conditions, it seems capable of playing a very important rôle in denudation. Passarge has shown that under conditions of long-continued aridity in an inclosed basin remarkably even plains may be developed over large areas by this agency combined with the action of occasional rains, which by washing loose material into the hollows tend to counteract any tendency on the part of the wind toward the formation of basins in the areas of the more easily eroded rocks. Plains of such an origin with harder rock-masses standing above them as "Inselberge" are described from South Africa. In so far as the smooth plain condition and the occurrence of monadnocks projecting above it is concerned the conditions observed in the Rock Springs region agree with the wind-erosion hypothesis. Another condition which is in harmony with this interpretation is that the rock floor of the peneplain underneath the gravels, wherever observed, was found to be fresh and undecayed. There was no evidence of an old soil underlying the gravels such as might be expected if the planation were performed under moist conditions. It is possible however that any old soils which may have been formed were removed during an arid period just preceding the deposition of the gravels.

While the features of the peneplain may be interpreted as due to wind erosion, the writer is inclined to favor the hypothesis of subaërial denudation under moist conditions. The reasons for this preference are as follows: (1) Present conditions in the region indicate only a moderate efficiency of wind erosion. The region at the present time is subjected to desert conditions, though these are not now extreme. The winds are strong and blow almost continually, especially during the day. Wind action is conspicuous in places where conditions are particularly favorable, and a very considerable amount of material is removed in this way, yet the present features of topography are due rather to stream work than to the wind. In places where the streams by cutting have exposed softer rocks and these are of such a nature as to be easily eroded, wind scour is noticeable, but otherwise not. Practically all the details of topography are the result of water action. In southern California where the average rainfall is less than five inches per year the topography is almost entirely the result of stream action. There is even less evidence of wind work than in Wyoming. All the dissection of the mountains is of the type produced by streams and there is little sign of wind erosion. It is true that the winds do pick up and carry away considerable dust at certain times, particularly during dust storms, but their topographic effect as compared with that of desert streams is almost negligible. For these reasons the formation, by wind erosion, of a smooth peneplain like that under discussion seems without parallel in present conditions. (2) The conditions round the base of Aspen Mountain are thought to indicate a moist climate at the time of planation. Those conditions are indicated by the accompanying sketch, Fig. 7. At the time of its development the peneplain extended with gentle slope close up to the base of the mountain. Later, under conditions of undoubted aridity, a mantle of piedmont gravels accumulated round the base of the mountain. Since the arid climate brought about the formation of the wash-apron it would seem that at the time of planation the climate must have been moister, for material resulting from weathering was then removed and the peneplain developed close up to the hard rocks of the mountain.

The basis of the assignment of the accumulation of piedmont

gravels to an arid climate is this—under such conditions whatever rainfall there is usually comes in the form of torrents or cloudbursts. These give a very heavy precipitation over local areas for a short time, with resulting temporary streams of great transporting power. These occasional torrential rains act on slopes unprotected by vegetation and consequently pick up and carry forward a heavy load of rock-waste. Just as soon as the streams leave the steeper slopes much of this débris must be dropped, and all must come to rest within a comparatively short distance, for the water either sinks into the ground or rapidly evaporates. The consequence of this process is the accumulation of piedmont gravel slopes round the higher lands. Under a moist climate the streams are perma-

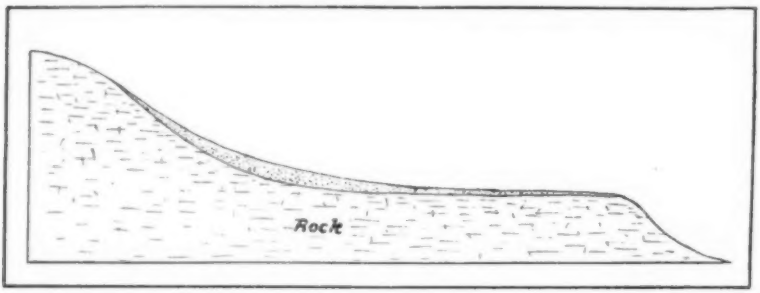

FIG. 7.—Sketch showing conditions round the base of Aspen Mountain. A lens-shaped débris fan mantles the lower slopes.

nent, they work continuously; the slopes are protected by vegetation, hence furnish less débris to the waters of a passing storm. Weathering reduces the rocks to finer particles, which are exported by the ever-flowing streams, consequently degradation rather than aggradation is the rule. It is believed that under these conditions planation, with the removal of the resulting waste, would be pushed close up to the base of the harder rocks.

This, as an explanation of the conditions round Aspen Mountain, is not without its uncertainties, for it might be argued that conditions of extreme aridity might allow the development of a flat or gently sloping plain close up to the base of the mountain by wind erosion. In that case the efficiency of the wind in removing loose débris from round the base of the mountain must have been

greater than that of the temporary streams in loosening and carrying material down the slopes, for any such piedmont débris must be removed before the wind can attack the rocks at the mountain-base. In an absolutely rainless region there would be no difficulty in accepting this explanation, but there seems to be no region which is without its occasional rains, and a slight amount of rainfall distributed as it is in the deserts in the form of local torrents would be sufficient to bring down a considerable quantity of débris from the bare slopes of the mountain—more it would seem than could be effectively disposed of by the wind.

From the foregoing lines of reasoning it is thought that the planation was the result of long-continued subaërial denudation under conditions of a moist climate. This belief is not held with great confidence, however, for it is recognized that desert erosion might under certain conditions produce similar results.

The surface of the gravels, from Miller Mountain northward to near the low area, slopes to the north at the rate of between seventy and one hundred feet per mile. The underlying rock-surface has a slightly lower slope. Judging from the present slope and attitude of the gravel-deposits it seems unlikely that there has been any considerable change in slope of the underlying peneplained surface since they were laid down, though there may have been a general elevation of the whole region. The gravel surface is a graded slope and shows no sign of disturbance since its formation. The transportation of large bowlders such as those on Miller Mountain would require a considerable gradient, probably as great as that at present. On the other hand, the development of a peneplained surface as even as that under discussion would require a more nearly horizontal attitude than at present at the time of planation, at any rate if this were accomplished under conditions of a moist climate, as there seems reason to think was the case. Whether or not such a surface with such a slope could be formed under desert conditions by wind scour is more difficult to determine, but it seems unlikely. The present slope would therefore indicate that, unless planation was the result of wind erosion, this portion of the peneplain when formed was more nearly horizontal than now and that it was tilted toward the north at a time of

renewed uplift of the Uintas immediately antedating the deposition of the gravels.

Cause of the invasion of the gravels.—The gravels which form the capping of the peneplain were, in the southern part of the area, unquestionably derived from the Uintas. During the long period of quiet while the peneplain was developing, any considerable elevations in the Uintas must have been considerably reduced and very possibly planed off to correspond with the character of the adjoining country. At any rate they were not then supplying débris to the adjacent low-lying areas.

In order to bring about the change from these conditions to those which followed, in which great desert fans spread out from the mountains and covered the adjacent plains to distances of from thirty to forty miles or more, there must have been a decided change in the relations of plains and mountains. A change of conditions capable of producing so great results could have been no less than a pronounced renewed uplift of the Uinta mountain-range with the consequent development of extensive débris fans.

As a test of the preceding, let us postulate conditions as they seem to have been at the end of the period of planation, with the whole country, including the Uintas, reduced to low relief and lying at a comparatively low altitude. What then would be the effect of a marked uplift of the mountain-range?

In the first place there would, in all probability, be a marked change in climate. The high mountain-range to the south would cut off some of the moisture-bearing winds; with the result that the adjacent lowlands would become more arid. This effect would be increased if at the same time the Wasatch range, which runs north and south about one hundred miles west of this area, were also elevated so as to cut off the winds from the west. The high lands of the Uintas, attacked by the agencies of denudation and receiving most of the precipitation, would supply to the streams large quantities of rock-waste which, on account of the arid nature of the climate, could not be entirely removed to the sea, but would accumulate at the base of the range in the form of alluvial fans such as are developing at the base of the desert-ranges today. These fans as they grew would gradually spread out over the

peneplain to the north, burying first the region close to the base of the mountains and later that farther away. In the meantime these more distant parts would be exposed to the agencies of an arid climate until the fans finally reached them. We should expect to find then along this outer zone not a deep residual soil formed during the time of planation, but fresh rock floors resulting from exposure to an arid climate before the fans reached so far out.

The effect of an arid climate on a monadnock like Aspen Mountain should be apparent in the mantling of the slopes with débris. This, owing to the lack of a protective covering of vegetation on the slopes, would be comparatively rapidly carried down by the desert torrents and accumulated at the base as has already been suggested. This is the actual condition at the base of Aspen. Starting at the low area and going toward the mountain one finds that the gravel-deposit is all of local nature and gradually thickens till, near the base of the mountain, it has an observed thickness of over two hundred feet and the base was not seen. It thins again as it laps up on the sides of the mountain. The section radially to the mountain is lenticular in form, the bottom corresponding to the rock-slope of Aspen as developed during the time of planation, and the top being graded to the slope of the desert fans, which is considerably more gentle.

The bed-rock in the low area is fresh, as already stated; a condition which agrees equally well with the succession of events just postulated, as with the idea of planation under desert conditions.

The relation of the Miller Mountain gravels to the Uintas corresponds in all respects with what we should expect in the case of gravel fans accumulating at the base of high mountains in an arid climate, not only in the nature of the material in the fans, but also in the distribution and general attitude of the deposits.

Reasoning thus we are led to the conclusion that the period of planation was brought to a close by a renewal of mountain uplift during which the Uintas were greatly elevated with respect to the surrounding plains; that this period of mountain-making was probably followed in this region by a change from a comparatively moist to an arid climate; and that great desert fans of gravel and

sand spread out from the mountains far over the plains, while at the same time smaller fans spread out in like manner from the monadnocks of the plains and merged with the gravels from the mountains.

It seems likely that this mountain uplift was accompanied by tilting of the land for twenty miles or so north of the mountains, for, as stated already, the rock-surface over this area slopes toward the north at the rate of about seventy-five feet per mile; a slope which seems too great to have remained undissected under the conditions of planation.

The Uintas at the time of the deposition of the gravels rose to a much greater height than at present, for to the south of Little Mountain and Miller Mountain the present summits of the range are little if any higher than the base of the gravels on these plateaus. The highest summit north of Green River is about 8,250 feet, while the summit of the plateau at Miller Mountain is 8,500 feet and Little Mountain is still higher. South of the river the mountains are somewhat higher, but even here they are only fron 300 to 1,000 feet above the tops of the gravel-capped plateaus. This in a distance of from fifteen to twenty-five miles gives a slope entirely inadequate for the transportation of the coarse gravel found on Miller Mountain. If the present grade of the gravel surface on Miller Mountain, one hundred feet per mile, were prolonged for fifteen miles it would amount to a rise of 1,500 feet. This is not enough, for the fans were necessarily steeper near the mountains than farther out so that at the very least the mountains must have been 2,000 feet higher than now to give sufficient grade to account for the transportation of the gravels to their present position, and this is not taking into account the still greater elevation necessary to furnish a supply ground for the material of the fan.

The course of Green River during this time of mountain-building cannot be discussed here, as its relation to the gravels close to the base of the mountains is not known to the writer. At present it flows between the gravel-deposits of Miller and Little mountains and the higher parts of the Uintas from which the gravels were derived. We are led then to one of two alternatives: either the river was not flowing in its present course at the time the gravels

were deposited, or the gravels were derived entirely from the part of the mountains north of the river. Further observations will be necessary to determine this point. It is suggested that a study of the relations of the river and gravels in and near the mountains is likely to furnish valuable clues toward the solution of the problem of the history of Green River and its relation to the Uinta Mountain uplift.

In connection with the evidence of the uplift of the Uintas at or near the close of the Miocene it is a significant fact that the lava-flows of the Leucite Hills were spread out on the surface of this Tertiary peneplain. Earth movements of great magnitude such as those responsible for the uplift of the Uintas are likely to be accompanied by volcanic activity, either in the area of uplift or in neighboring regions. With this fact in mind it would seem more than a coincidence that the Leucite Hills lavas were extruded at about the time of the building of the outwash gravel fans from the newly uplifted Uinta Mountains; since both fans and lava-flows lie on the undissected surface of the peneplain. In this connection it is interesting to note that in the Sierra Madre about one hundred miles to the east Ball[1] has found high-level gravels similar to those of the Rock Springs region, in some places overlain by lava-flows.

Studies in the West[2] have shown that the close of the Miocene or more probably the transition period between the Miocene and the Pliocene was a time of extensive mountain uplifts and crustal movements. The Tertiary peneplain of the Colorado valley was, according to Dutton,[3] uplifted at this time. Large parts of the Great Basin and the Sierra Nevada and Cascade mountains were elevated. It was at this time that the topographic features of the West began to take shape somewhat as they are today. There occurred over the whole Cordilleras a regional uplift as well as one of individual mountain-ranges. Coincident with these crustal movements were the great lava-extrusions of the late Miocene.

[1] Max W. Ball, "The Eastern Part of the Little Snake River Coal Field, Wyoming," *U.S.G.S. Bull. 381*.

[2] See Chamberlin and Salisbury, *Text Book of Geology*, III, 274–75, for references.

[3] Dutton, *Monograph II*, U.S. Geol. Survey.

The fact that the succession of events indicated by the gravel-covered peneplain with its associated features, as worked out independently of these other studies, agrees so closely with their results, strengthens the conclusions reached as a result of our local investigation.

PHYSIOGRAPHIC CHANGES SUBSEQUENT TO THE GRAVEL-DEPOSITION

1. *Erosion.*—Practically all the erosion which gives rise to the present diverse topography of the Rock Springs region is subsequent to the deposition of the gravels. Over wide areas these are entirely removed, and wherever present they are merely remnants standing, in general, over 1,000 feet above the major stream-valleys. The present streams, which over the area once covered by the gravels must have been initiated on the gravel surface, are superposed discordantly on the underlying rocks. The minor tributaries are subsequent on the structure, while the major streams are entirely independent of it. In one instance, that of Salt Wells Creek, the stream three times breaks across a scarp over 1,000 feet in height. Wide areas in the softer rocks have been reduced to low relief at elevations from 800 to 1,000 feet below the old peneplain level. Except where protected by lava-flows or the gravels, even the tops of the scarps of harder sandstone are several hundred feet below the peneplain level. All of this erosion has taken place since the deposition of the gravels.

Present denudation is being accomplished by wind and water together. The hardness and position of the rocks are the determining factors in the rate of erosion. In general the harder rocks stand out in the form of scarps. Horizontal rocks have shown greater resistance than the same rocks in an inclined position.

As already pointed out, the Uinta Mountains from which the gravels were derived are now lower than the tops of the gravel-deposits fifteen miles and more away and are separated from them by a valley at least 2,500 feet deep (see photograph, Fig. 8). They must therefore have been subjected either to profound denudation since the gravels were spread out over them, or to downthrow by faulting. If their present low elevation is due to denudation this

must have been relatively much greater than that of the gravel-capped plateaus. This is not unreasonable, for one would expect that denudation would be more effective in the mountains, exposed as they are to the excessive action of frost and wind, with steep slopes and highly inclined rocks, than in an adjacent lower region of nearly horizontal rocks, even though the rocks in the mountains are harder. Then too, in the case of the Uintas, Green River flows through them in a deep canyon. This gives steep slopes and con-

FIG. 8.—A typical exposure of the conglomerate on the south face of Little Mountain. This is a view looking southeast into Red Creek basin, the bottom of which lies some 2,500 feet below. The outlying ranges of the Uintas may be seen in the background to the right. Red Creek valley lies between the plateau and the mountains. This view gives some idea of the character and immense amount of erosion which has been accomplished since the conglomerate was laid down. (Photo. by A. R. Schultz.)

sequently more rapid erosion of the adjacent mountains than of the plateaus farther away. As to the alternative of a downthrow of the mountain-block since the gravels were deposited, there is some uncertainty. The principal uplift of the northern flank of the Uintas took place along a fault whose maximum displacement amounted to over 25,000 feet, but there seems to have been a certain amount of downthrow as well as uplift along this fault-zone. Powell[1] described such a downthrow running in an east-and-west direction south and southeast of our area, which he believed had lowered the mountain-block by from 1,000 to 3,000 feet in various

[1] Powell, *Geology of the Uinta Mountains*, 204–6.

places along the fault-line. This fault is described as displacing beds of the Brown's Park Tertiary, but since these beds have been considered to be of earlier age than the Bishop Conglomerate, there is no evidence to indicate the exact time of the displacement; whether before or after the development of the conglomerates.

It is therefore impossible to determine from the data at hand whether the present low elevation of the eastern end of the Uintas, relative to the gravel plateaus, is the result of down-faulting or of simple denudation, with a more rapid lowering of the tilted rocks close to the deep canyon of Green River than of the gently sloping gravel-capped plateaus farther away. Whatever may be the final decision of this point, there can be no question as to the profound denudation subsequent to the gravel-deposition. Red Creek basin, over 2,500 feet deep, and lying outside of the faulted zone, gives a fair measure of this denudation.

The period of erosion continued until all the valleys of the region were deeper than they are at present, though just how much deeper is not known. This erosion evidently took place under conditions of a moderately moist climate, for great amounts of material have been removed by the rivers. A desert climate favors accumulation rather than removal.

2. *First period of aggradation.*—After this period of degradation there came one of aggradation, during which the valleys were partly filled by deposits of silt and gravel washed down from the valley-sides. On the west side of Salt Wells Creek, along and south of Pretty Water Creek, there is an extensive wash-apron derived from the high, gravel-capped Miller Mountain plateau. This wash-apron mantles the slopes down to the valley-bottom, where it grades into a flat-topped valley-filling which now remains as a distinct terrace about forty feet above the present stream (Fig. 9). This valley-filling must have had a depth of considerably over forty feet, for bed-rock is nowhere exposed in the stream-bottom. At least one hundred feet is thought to be a moderate estimate. There are no wells to indicate its exact depth.

This period of aggradation is referred to a change to a more arid climate than that under which the major erosion was accomplished. Under arid conditions the occasional torrential rains, acting on

slopes unprotected by vegetation, loosen and bring down heavy loads of débris, which the streams, on account of their intermittent character and the rapid dissipation of the water after a shower by evaporation and absorption into the dry soil, are unable to carry out of the valleys. The result is the silting up of the valleys and the formation of alluvial fans and wash-aprons on the slopes. On the return to a moister climate the streams become permanent, the land is protected by vegetation, hence furnishes less débris to the waters of a passing storm, with the result that the wash-aprons and

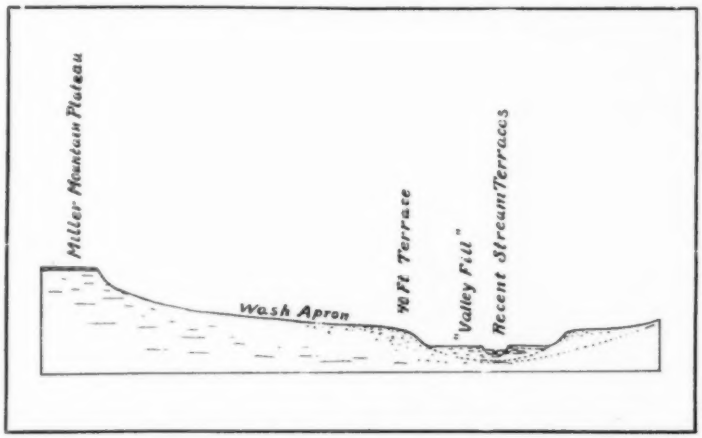

FIG. 9.—Sketch showing conditions along Salt Wells Creek. This sketch shows all the terraces referred to in the text, and their relations to each other and to the Miller Mountain plateau. Vertical scale exaggerated.

silted valleys built up under arid conditions are dissected, leaving gravel terraces along the stream courses.

3. *Erosion.*—Following the preceding stage of desiccation and aggradation there came one of erosion when the wash-aprons were dissected by the streams and the gravel and silt deposited in the central part of the valley were cut down, leaving remnants as flat-topped terraces on either side. This feature is best shown along Salt Wells Creek from the junction of Pretty Water Creek to Chimney Rock, about two and one-half miles to the north. There a cut from one-fourth to one-half mile wide has been made through

the silts and gravels. The resulting terrace is from twenty to forty feet in height and is clearly marked. At the point where the wash-apron feature is best developed, south of Pretty Water Creek, the minor topography is entirely subsequent to the wash-apron, which forms partly dissected, flat divides between the streams. This period of erosion and dissection of the gravels is referred to a cessation of the arid conditions and a return to a moister climate.

4. *Second period of aggradation.*—The full extent of the dissection of the preceding period cannot be seen, for a second period of aggradation has followed and the bottoms of the stream-valleys have again been silted up to an unknown depth. This is the "valley-fill" of the present streams. All the streams, large and small, of the Rock Springs region have this filling which varies, according to the size of the stream, from a few feet to more than a mile in width. The material of this "valley-fill" is a sandy loam with many of the characteristics of loess. It stands up in vertical cliffs along the stream-trenches, sometimes to a height of twenty feet.

The aggradation responsible for this valley-fill is thought to be due without question to a change to more arid climatic conditions. In one of the narrow valleys cut through the high sandstone scarp west of Salt Wells Creek the filling progressed until the bottom of the valley was changed from a graded stream-bed to a series of fans which entirely destroy the grade along the valley-bottom. It is plain that such an effect could be produced only in an arid climate. In this case the valley was small and evidently, during the arid period, could not support even a temporary stream.

5. *Present period of slight dissection.*—In the case of the valley just described the stream is at present cutting through the fans and has almost succeeded in bringing its bed down to grade again. The stream now flows only in times of flood, so that this action is not rapid. All the streams of the region are beginning the dissection of the "valley-fill." Along the larger ones a series of distinct terraces is forming (see Fig. 10). These are migrating up stream. Three terraces in the lower course of a stream give place to two higher up and to a single trench still higher. In several places the mode of retreat was noted. It is by a fall from one or two to five

or six feet in height. All things point toward the conclusion that this dissection is still in progress.

A slight increase in precipitation is thought to be the cause of the dissection. What but a change in the amount of rainfall would account for the building of desert fans across a small stream-valley and their subsequent dissection by the stream?

Confirmative evidence of recent increased precipitation is furnished by a belt of sand dunes about forty miles north of Rock Springs. This belt of dunes begins in the broad plain of the valley of Big Sandy Creek near its junction with Green River, and extends eastward through a low gap in the scarp west of the Leucite Hills,

FIG. 10.—Looking across Salt Wells Creek toward Chimney Rock, showing the flat "valley-fill" in which the stream is developing a series of terraces. Three distinct terraces are found at this point. The view gives a good idea of the general character of the flats formed during the latest period of aggradation. Chimney Rock is nearly one-half mile distant, and the flat is here over one-quarter mile in width. (Photo. by B. L. Johnson.)

between two of the larger of these, Steamboat and North Table, and thence eastward across the plain of the Red Desert for many miles. The belt of dune sand varies from one or two to five miles in width. All along the dune strip the vegetation is encroaching on the dunes. In crossing from one side to the other, one passes first an area from one-fourth to one-half mile in width of stagnant, sage-covered dunes, then a belt of active dunes with almost no vegetation, and finally on the other side another belt of sage-covered dunes. West of the pass, on the plains of the Green River valley, the strip of active dunes rapidly narrows to a wedge which pinches out about four miles west of the pass. Here, and farther

west as far as one can see, there is still the dune strip three or four miles wide, but all is covered with vegetation. The irregular dune topography still remains and in places is as well developed as in the area of actively moving sand. Sage brush, often as high as a man's head, covers the dunes.

It is evident that at the time these dunes were forming, the climatic conditions must have been different than at present. A change, either to greater precipitation or lowered mean temperature, or both, with consequent lessened evaporation, would allow vegetation to gain a foothold on the dunes.

This, taken in connection with the fact that the streams are now dissecting the valley-filling formed during a previous dry period, is strong evidence of recent increased precipitation, or, what amounts to the same thing, a cooler climate with lessened evaporation.

It might perhaps be argued that the series of terraces found along the streams could be due to changes in level of the land rather than to changes in climatic conditions. To account for the terraces on this basis would necessitate the following series of crustal movements: First, elevation during the first great erosion; second, depression to account for the first period of aggradation; third, elevation to account for the second period of erosion below the bottoms of the present streams; fourth, depression to account for the second period of aggradation and the formation of the "valley-fill"; and fifth, another slight elevation giving rise to the present stream-trenching. Such an explanation necessitates too many unproved crustal movements.

Relative lengths of the periods of terrace-formation.—It must not be supposed that all these different periods of aggradation and dissection were of equal duration or importance. By far the most important event since the deposition of the high-level gravels was the long cycle of erosion which produced the dominant features of the present topography. All the later terraces are minor features developed within the larger valleys resulting from this great erosion, and represent comparatively recent climatic fluctuations. Fluctuations of equal or greater magnitude might have occurred while the great erosion was in progress without leaving any surviving record.

Comparison of other observations bearing on the problems presented in this paper.—Both King[1] and Powell[2] described the high-level gravels of this region—King, under the name of Wyoming Conglomerate, and Powell under that of Bishop Mountain Conglomerate. Powell recognized the true nature of the gravels as well as the peneplained surface on which they lie. He writes:

> The Bishop Mountain Conglomerate is found at different places to lie unconformably upon every group of the table which is represented in the Uinta Mountains and adjacent country. Its plane of demarkation represents a cessation of the movements of displacement in the region over which it is found, and that the same region was planed down to a base-level of erosion, which base-level was continued during the accumulation of these beds, for it is believed to be a subaërial conglomerate; but should further evidence prove it to be a subaqueous accumulation the plane of separation would then represent an epoch of change from a period of erosion to a period of deposition.[3]

As to the mode of accumulation he has this to say:

> I think that many geologists would ascribe this conglomerate to the action of ice, but throughout all that portion of the Rocky Mountain region which I have studied, I have so frequently found gravels and conglomerates of subaërial origin, and have in so many cases found reason to change my opinion concerning them, often having attributed a driftlike deposit to glacial action, and afterward, on further study, abandoned the theory, being able to demonstrate its subaërial origin, and witnessing on every hand the accumulation of such gravels in valleys and over plains where mountains rise to higher altitudes on either side, and having in so many cases actually seen the cliffs breaking down and the gravels rolling out on the floods of a storm, I am not willing to disregard explanations so obvious and so certain for an extraordinary and more violent hypothesis.[4]

Hayden in connection with his "Survey of the Territories"[5] reports high-level gravel-deposits similar to those of Miller Mountain as occurring on Table Mountain, an isolated butte southeast of the Wind River range; in the valley of South Pass; and along the

[1] Clarence King, *Explorations of the 40th Parallel.*

[2] J. W. Powell, *Geology of the Uinta Mountains*, U.S. Geol. and Geog. Survey, Division II.

[3] J. W. Powell, *Geology of the Uinta Mountains*, 62.

[4] *Ibid.*, 170.

[5] Hayden, *U.S. Geol. and Geog. Survey of the Territories of Idaho and Wyoming, 1877*, 133.

Seminole Mountains. Darton[1] describes flat-topped deposits of coarse conglomerate capping some of the higher divides of the Bighorn Mountains of Wyoming. As already stated, Woodruff[2] finds similar gravels in the Wind River basin, and Ball along the flanks of the Sierra Madre. It is highly probable that further work will demonstrate that all these deposits are genetically related and are the results of the same set of widespread physical conditions.

The later stream-terraces developed in the valleys of the Rock Springs region are thought to be susceptible of correlation with the fluctuations in size of the lakes of the Great Basin, particularly of Lake Bonneville as worked out by Gilbert.[3] Gilbert's succession follows:

1. Pre-Bonneville low-water epoch. This was of long duration.
2. First epoch of high water.
3. Interval of low water, probably with complete desiccation.
4. Second epoch of high water. This was only about one-fifth as long as the first of the high-water epochs.
5. Post-Bonneville epoch of low water, continuing until recent times.

When the succession worked out from the Rock Springs stream-terraces is compared with this it is found that, beginning with the present and working backward, the long period of erosion following the deposition of the high-level gravels on the plateau includes Gilbert's first epoch of high water. From that to the present the two agree closely, the periods of aggradation corresponding to the epochs of desiccation of the lakes, and periods of erosion corresponding with the epochs of high water.

It is believed that, as in the case of the Great Basin lakes, the climatic changes recorded by the stream-terraces are to be correlated with those of the Pleistocene glacial epochs. No glaciers invaded any part of the drainage-area of the Rock Springs region, consequently *the evidence furnished by stream-terraces is entirely free from complications arising from the presence of outwash glacial gravels.*

[1] N. H. Darton, *U.S. Geol. Survey, Professional Paper No. 51*, 67–70.

[2] *Loc. cit.*

[3] G. K. Gilbert, "Lake Bonneville," *U.S. Geol. Survey, Monograph 1.*

SUMMARY

The succession of events indicated by this study is as follows:

1. *Planation*, in progress during the latter part of the Tertiary, reduced the Rock Springs region, including all the area from the Uinta Mountains to the northern end of the Leucite Hills, to the condition of a peneplain of very even surface surmounted by a few small monadnocks of especially resistant rocks. This peneplain is possibly to be correlated with that of the high plateau country to the south in Utah and Arizona.

2. *Mountain-building.*—Pronounced orogenic movements in the late Miocene or early Pliocene brought the foregoing period of planation to a close. These movements resulted in a very considerable renewed uplift along the Uinta mountain-range and a general elevation of the whole region. A change to a more arid climate than formerly is also indicated. Extensive waste slopes or desert alluvial fans were developed round the base of the mountains, and spread far out over the adjacent plains. A remnant of this desert-fan deposit forms the Bishop Conglomerate described in this paper.

3. *Erosion.*—A long period of erosion, probably with a moderately moist climate and relatively steep stream-grades, gave rise to the present diverse topography. Subsequent to the deposition of the gravels, erosion or faulting reduced the height of the Uintas so much that parts of the mountains which must have supplied the gravels now lie at levels lower than the tops of the gravel-beds fifteen to twenty miles away.

4. *Aggradation.*—A change to arid climate brought about a cessation of erosion and a change to conditions of aggradation. The stream-valleys were silted up, and extensive wash-aprons developed at the base of the steeper slopes.

5. *Erosion.*—A return to moister climate resulted in the partial dissection of these wash-aprons and valley-gravels, producing terraces along the valley-sides.

6. *Aggradation.*—Another change to aridity resulted in the formation of the "valley-fill" of the present streams. Some smaller stream-valleys with steep side slopes were partially choked and the stream-grade destroyed by desert fans.

7. *Erosion.*—A recent slight increase in precipitation is indicated by the renewed cutting by the streams and by encroachment of vegetation on the sand dunes.

Conclusion.—In conclusion it is suggested that future correlations of the high-level conglomerates, as well as of the later terraces in the stream-valleys, can be most satisfactorily made on a genetic basis. It will, in most cases, be impossible to trace these features from one drainage-system to another directly. The only basis for comparison is that, in general, like conditions will produce like results, and if the conditions affect large areas, as for instance climatic changes or great periods of planation or mountain-building, their results will be equally widespread.

CONTRIBUTION TO THE PETROGRAPHY OF THE KEWEENAWAN[1]

FRANK F. GROUT
University of Minnesota

OUTLINE

INTRODUCTION
GEOLOGY: Surficial
Relations
Structure
Areal
Economic
PETROGRAPHY: Review
Clastic Rocks
Types of Igneous Rocks
Mottled Diabase
Hackly Diabase
Conchoidally Fracturing Diabase
Porphyritic Variations
Glasses
Amygdaloidal Textures
Amygdules and Other Secondary Rock Minerals
Chemical Classification

INTRODUCTION

The effusive and clastic rocks of the southwestern extreme of the Keweenawan area, reaching into Minnesota, have been the subject of new study, more detailed than is reported in previous papers.[2] The main results are of two kinds, detail of outcrops, and a laboratory study of rock types and minerals, the latter of more general interest than the former. The new detail reveals no great error in the general maps recently published, but the map here presented shows the

[1] By permission of the Minnesota Geologic and Natural History Survey.

[2] R. D. Irving, "Copper-bearing Rocks of Lake Superior," *U.S.G.S. Mon. V*; Warren Upham and N. H. Winchell, *Minnesota Geol. and Nat. Hist. Survey*, II and IV (county reports); C. P. Berkey, "The Geology of the St. Croix Dalles," *American Geologist* (1897); C. W. Hall, "The Keweenawan Area of Eastern Minnesota," *Bull. Geol. Soc. Am.*, XII, 313.

region of new work, the exposures northeast of Kettle River being now mapped for the first time. The Keweenawan extends not over thirty miles west of the state line, and seventy miles north and south. Maps on a more accurate scale will be given in the reports of the survey when published.

Acknowledgments are due to Professor C. W. Hall for the conception of the work, and to Messrs. A. W. Johnston and W. Yeaton for field assistance.

GEOLOGY

SURFICIAL.—No detailed attention was given to the glacial features of the area, but in passing, it was seen that a great moraine occupied the southeastern side of Pine County, and that the tributaries of the St. Croix River cut through a great thickness of red sandy gravel. From this red drift, just south of the St. Croix, Dr. Berkey describes a laminated red clay, from the study of which he draws important conclusions as to the years that elapsed between two advances of glacial ice. No greater exposures were found than those described by Dr. Berkey, but the boundary including all such clays found in Minnesota indicates that the area is about four times as great as he explored (see Fig. 1).

RELATIONS.—To the south, Upper Cambrian sediments lie unconformably over the lavas of the Keweenawan. To the west and north, the lavas are in contact with more indurated sandstone, in a fault, the mapping of which has not been much altered by the discovery of new exposures. The correlation of the sandstone south on the St. Croix, with that northwest of the fault, is considered safe, but left uncertain by the fact that fossils are not known from the latter, by the unknown extent of the faulting movement, and even the direction of that movement. The dip of both sandstone and lava for several miles from the fault is southeasterly, as would be expected from an elevation of the sandstone, but observations close to the fault are few, and the rocks in these cases badly shattered. When the same contact is traced northeast into Wisconsin, clearer evidence points to a depression of the sandstone, and this is probably the best evidence of conditions in Minnesota.

STRUCTURE.—Within the Keweenawan some of the structure is equally uncertain on account of the scarcity of good exposures.

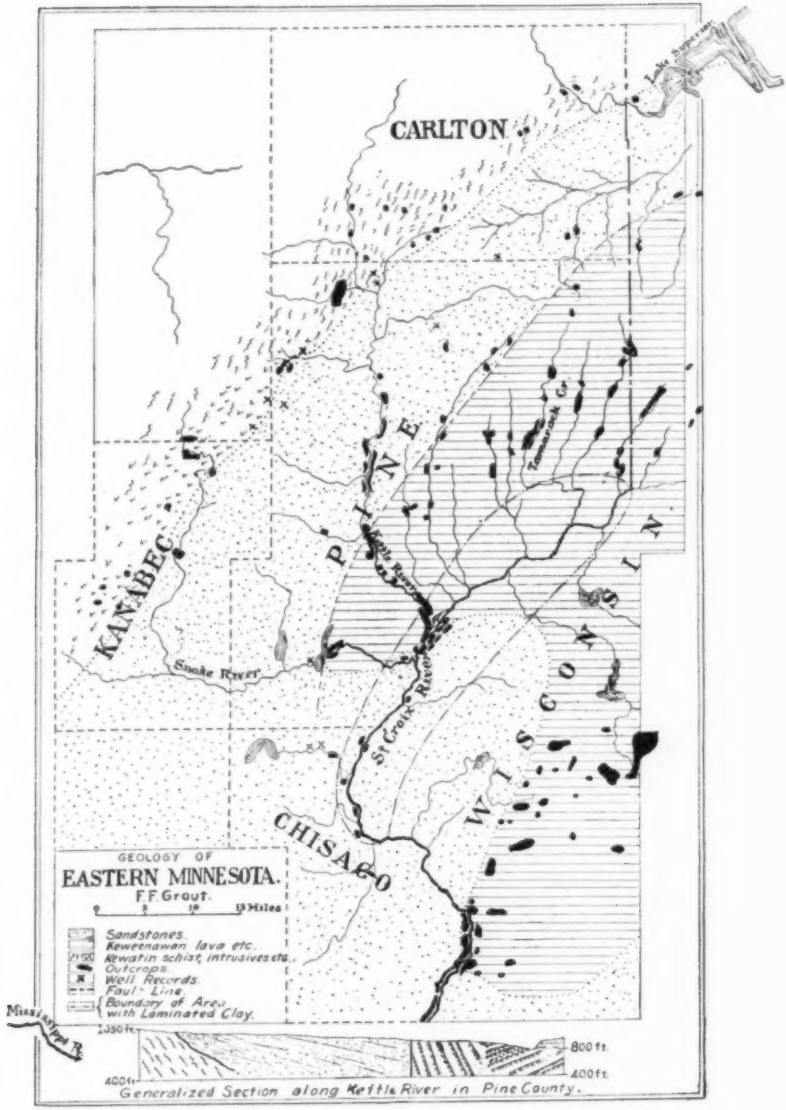

FIG. 1.—Map of eastern Minnesota and part of Wisconsin, showing outcrops and general geology.

Petrographically there is little that is new to the Keweenawan. The greater part of the rock originally occurred in surface flows, with an occasional conglomerate apparently formed along some shore-line. Beds of tuff, derived from volcanic ash and breccias, are not numerous, but are prominent in a few places. Intrusive dikes were not identified in this area. Evidence of the effusive nature of the rocks lies not so much in flowage structures as in the regular sequence of textures—a compact aphanitic basal portion grading into the

FIG. 2.—Ditch at Pine City, Minn., showing lava flows dipping 67°. Flows may be distinguished by the changes of the jointing in the amygdaloid.

coarser body of the flow, with often a characteristic amygdaloid breccia or ash bed before the next flow repeats the series. The jointing is in most places irregular, but in some columnar, as, for example, that producing the Devil's Chair at the Dalles of the St. Croix. The main jointing seldom persists into the amygdaloid, thus giving another means of distinguishing successive flows (see Fig. 2). The chief evidence of faulting is the development of slickensides in several places, and these may be along very minor fractures due to the extensive tilting of so thick a formation. There are no signs of the erratic discontinuance of a flow, or a shifting of position. Spheroidal weathering is quite common. Exceptional structures

develop locally; e.g., a banding simulating gneissic structure in a flow on Snake River, and a schistose streak a few inches wide in a flow seen by Berkey at Taylors Falls.

Near the fault the strike of the flows follows the fault quite closely. The general structure is a complex syncline. Beginning at the south, it is clear that the axis of the syncline must pass between the Taylors Falls rocks, dipping 15 degrees south, 70 degrees west, and the Snake River series, dipping 70 degrees south, 80 degrees east. On Kettle River the axis of the syncline is located within a few hundred paces. The flows farthest up the river, near the fault, dip 50 degrees south, 70 degrees east, and near the mouth other flows dip 20 degrees north, 70 degrees west. Near Kettle River the strike changes rather abruptly, swinging more easterly as one follows a flow northward. In this northeastern area no dip of more than 45 degrees was observed and no outcrop was found southeast of the synclinal axis. Some observations, however, indicate the proximity of the axis. In Wisconsin the axis was sketched by the early geologists,[1] running southwest close to the St. Croix, for a long distance, always on the Wisconsin side. To connect their observations with those on Kettle River requires a double curve in the axis, crossing the St. Croix near the mouth of Tamarack Creek. An alternative might be the suggestion that the sharp fold on Snake River, which becomes less sharp on Kettle River and still less on the next stream, gradually disappears to the northeast; and the whole may be a secondary fold in the northwest limb of the main Keweenawan syncline, which would then be nearly as Irving sketched it. No correlation of beds across the syncline has been possible. In the clear exposures of Kettle River series, several conglomerates are seen on the southeast and none on the northwest, but this may be an accidental disagreement in an incomplete series, because conglomerates are known on Snake River, west of the syncline.

AREAL.—The map (Fig. 1) shows the general region of outcrops. The three main types of lava distinguished in this paper are widely distributed and it cannot be said that any one of them is absent in any of the extensive series. Exposures are hardly clear enough to note any change in the general character from the earliest to the

[1] *U.S.G.S. Mon. V.*

latest flow exposed. About three strikingly peculiar types occurred in a few isolated outcrops and not elsewhere in the series. A line connecting the outcrops of a single type proves to run due northeast, conforming to the observed strike near by. Such data furnish the best evidence in Minnesota that a single flow is continuous for over 25 miles. The red laumontite pseudo-amygdaloid is so traced, and within two miles across the strike a highly porphyritic type runs parallel with it.

Geographically the area may be briefly summarized. The Taylors Falls and Snake River districts are discussed in earlier publications, but the remarkable freshness of one of the Snake River rocks is worthy of further mention. In the new area studied there are a few local variations. Most of the exposures are along creek banks. The rock types seen on the western side of the syncline on Kettle River are found due northeast on the smaller creeks. These types include the red pseudo-amygdaloid and a highly porphyritic rock on each creek. Along the lower parts of the eastern creeks the types vary somewhat, but seem to be local modifications rather than evidence of extensive changes of nature.

ECONOMIC.—Copper is found in small amounts in test pits on all the easily accessible streams. Its association varies—on Snake River where most explored, it is in laumontite, and on Kettle River, in prehnite. Some nice specimens are produced. In connection with the chemical side of this study of rocks, it was discovered that the fresh trap rock was the source of the copper. Indications are that the original lavas contained from 0.01 to 0.03 per cent of copper.

PETROGRAPHY

REVIEW.—Descriptions of Keweenawan rocks written between thirty and forty years ago have not been seriously questioned, though the method of naming rocks has developed greatly. All attempts, including this one, result in complex statements referring partly to original conditions, and partly to present altered ones. A summary and correlation of rock-names, in the literature, is given by A. N. Winchell,[1] so that the full list will be omitted.

Chemical data have been presented, in addition to field and micro-

[1] *Journal of Geology*, XVI, 765.

scopic results, by several authors, but only a few analyses are satisfactory for the application of chemical classification. These ancient basic rocks are so far altered in most places that the original can be only roughly estimated from the present composition. However, it seems clear that alteration results differently in different cases, and the average of several tests of a rock-type will give valuable indications of the quality of the magma. It is therefore worth while to

FIG. 3.—Weathered volcanic breccia. About one-half natural size

extend the chemical work, especially when material is very fresh, and analyses can be made quite complete.

CLASTIC ROCKS.—The conglomerates of this area have all been described in earlier papers and need no comment except that no correlation of beds has been possible, and that they give evidence that the bowlders were derived from both Keweenawan and older formations.

Tuff and breccia, of the type found by Dr. Berkey at Taylors Falls, was found on the two tributaries of Tamarack Creek (Fig. 3).

The breccia consists of angular fragments of amygdaloid suspended in a fine-grained fragmental matrix identical with the tuff; and not, as suggested by Dr. Berkey, suspended in the flowing lava or cemented by igneous material. The tuff is fine grained in most places, and the fragments angular; though rounded grains and water-sorting are not difficult to find. Alteration has produced a hard mass of quartz and epidote, an almost indestructible rock. Tuffs and breccias mark the boundary zone between two flows, though in a few cases fragments have been suspended in a later flow.

TYPES OF IGNEOUS ROCKS.—The rock-types described and pictured by earlier writers on the Keweenawan are not all represented in the lavas of eastern Minnesota. In fact, so few are represented that it is unnecessary to use as elaborate a table as A. N. Winchell presents in correlation of the early work. Of his types, based on modern petrographic usage, the area furnishes diabase and olivine diabase with some approaches to basalt and augite andesite, and the corresponding porphyries. In all the sections examined the essential of diabasic or ophitic texture was observed, viz., *the plagioclase needles formed before the augite.* This approaches a granular texture when augite is neither abundant nor coarse grained, but if the fundamental fact be kept in mind, all may be classed as modifications of diabase. No distinction is here drawn between augite and diallage; the presence or absence of olivine is of secondary importance like that of magnetite. The variation of the rock (or its alteration) is evidenced by the range in silica from 42 to 65 per cent. If reference is limited to this Minnesota area, the varieties are more clearly classified by varying texture than by the presence of olivine or other characters suggested by Mr. Winchell. The prevalent diabase is a quite uniform, compact rock with hackly fracture, coarse to fine grained (Fig. 4), grading, on one hand, by all degrees into a rock that is strongly luster-mottled (Fig. 5), also coarse to fine; and on the other hand, into a rock with clearly conchoidal fracture (Fig. 6), often red in color and usually fine grained. These field distinctions correspond to microscopic variations given below. They are to be correlated with Irving's "ordinary," "olivinitic," and "ash-bed" diabase, respectively, but are all included in Winchell's diabase and olivine diabase. All are easily accessible near Pine City, Minnesota.

FIG. 4.—The common type of diabase showing hackly fracture. About one-half natural size.

FIG. 5.—The weathered surface of luster-mottled diabase. About one-half natural size.

Mottled diabase.—This is probably the most easily recognized by the unskilled, from the fact that it invariably weathers to a color-mottling, and usually to pits or projections on the surface (Fig. 5). Colors depend upon the conditions of weathering. As a rule, the flows are thick, many of them weather spheroidally, and the amygdaloidal zone is not prominent. The latter point has made some occurrences seem more like intrusive than extrusive rock, but no such conclusion is forced upon one, here. Pumpelly's early description[1] has been widely accepted and its outline of the development of the rock is probably correct. He clearly presents the appearance of

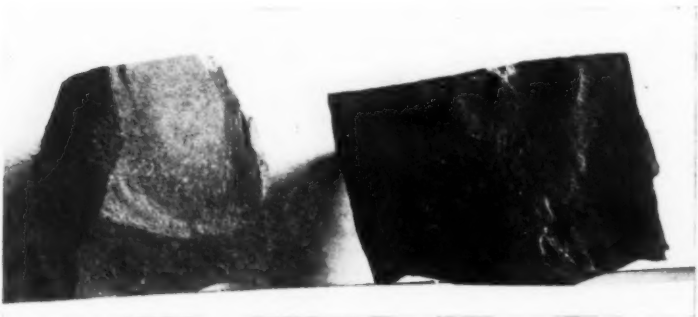

FIG. 6.—Conchoidally fracturing diabase. About one-half natural size

ophitic texture and the resultant luster-mottling. The original rock is reported as containing augite, plagioclase, olivine, and magnetite, with evidences of glassy matrix. Apatite is rarely seen. Alteration yields many other minerals. Of the fifty Minnesota rocks of this type, recently examined in detail, only one section revealed olivine cores of a size and freshness to yield an interference figure; but nearly all were well supplied with pseudomorphs, so similar to the fresh olivine as to be quite unquestionable, though the material was fibrous and pleochroic. Opaque minerals develop along the borders and cracks of the original grains, giving the impression of high relief to the alteration products, chlorite, serpentine, and iddingsite.

Magnetite is abundant in all sections. Hematite is prominent

[1] R. Pumpelly, *Geology of Wisconsin*, III, 33.

in some sections, chlorite in others, but the two seldom develop together.

The plagioclase is labradorite as determined by the maximum extinction angles, in sections perpendicular to the albite twinning. Zonal growth is not rare. The alteration of the feldspar is rather different from the average case described by Pumpelly. Prehnite is not a common product. Aside from a general dusty appearance, a granular light-green mineral develops in the central zone as if it were more easily altered than the outer zone. In extreme cases a complete pseudomorph results, faintly outlined in a ground-mass of no more definite character, and in the aggregate chlorite and orthoclase are indicated by analyses, if not optically. In a few cases secondary orthoclase crystals were identified. In a rather different alteration chlorite or some other green fibers grow up beside the feldspar as radiating groups, which encroach upon the lathlike grains, destroying their form and building a pseudo-amygdule.

Phenocrysts of plagioclase are neither common nor very large in the mottled rocks. When they appear, the composition is similar to that of the smaller crystals.

Augite is gray to brown, rarely showing the color due to titanium. It is one of the last minerals to be affected by alteration, which usually results in the borders becoming dark and dusty with chlorite. Rarely a pseudomorph occurs, light green, pleochroic, and with the extinction angles of hornblende.

In the coarser, fresher sections, the minerals that have been identified fill the space so completely that no room is left for glassy matrix, and none of the secondary products give the impression of resulting from such glass, or occupying its place. In the finer-grained parts of a flow—as near its base—a glass might be more probable, but even here are seen only the extreme alteration products and very little structure to indicate an original glassy condition. Another line of reasoning runs against the probability of much glassy matrix. Augite here appears to be one of the late crystallizations from the magma, and this mineral is commonly classed as a eutectic.[1] Hence it would begin to crystallize only after all those materials had separated, which made the fluid incapable of forming augite alone. It is hard to

[1] Cf. A. C. Lane, *Journal of Geology*, XII, 87–88.

understand how a matrix of the composition of augite should develop first some large crystals of that mineral, and later a glass of the same composition. The chlorite-like mineral which Pumpelly refers to glass, is admitted to be with difficulty distinguished from other chlorite in the rock.

TABLE I

ANALYSES OF MOTTLED DIABASES

1. Original type locality. Greenstone of Keweenaw Point, Mich. George Steiger, analyst. *Journal of Geology*, XVI, 765.
2. Taylors Falls, Minn., along railway track. F. F. Grout, analyst.
3. Tamarack Falls, Tamarack Creek, Pine Co., Minn. F. F. Grout, analyst.
4. Upper Tamarack Creek, Minn. Weathered red. A. W. Johnston, analyst.
5. Upper Tamarack Creek, Minn. Weathered green. A. W. Johnston, analyst.

	1	2	3	4	5
SiO_2	47.69	48.88	47.82	48.07	46.99
Al_2O_3	16.02	16.39	18.52	19.02	21.15
Fe_2O_3	2.41	5.51	6.39	7.65	7.14
FeO	8.70	7.21	3.15	4.83	3.94
MgO	8.31	5.80+	8.20	3.30	2.73−
CaO	10.54	9.11	11.09	9.84	2.17
Na_2O	2.44	2.08	1.67	2.84	0.80
K_2O	none	0.47	0.17	0.63	6.12
H_2O-	0.44	0.19	0.66	0.43	1.30
H_2O+	2.04	2.15	1.53	1.69	6.32
TiO_2	1.38	1.84	0.78	1.72	0.92
CO_2	none	0.09	0.17	none	none
P_2O_5	0.06	0.10	0.05	none	0.56
S	none	0.05	0.04	0.11	0.14
CuO	....	0.02	trace	....	....
MnO	0.26	0.15	0.12	0.21	0.12
BaO	none	0.02	0.02	0.02	none
SrO	none	none	none	0.02	0.03
Cr_2O_3	....	none	0.03	0.18	0.06
	100.29	100.06	100.41	100.56	100.49
Specific gravity	....	2.974	2.898	....	....
	*Auvergnose	Hessose	Hessose	Hessose	....

* For the significance of these names see *Journal of Geology*, X, 555.

The alteration was Pumpelly's special study[1] and proved interesting and complex. For details of the several successive changes, reference must be had to the original. The chloritic minerals are of greatest interest, and their nature is variable in each of the several types of occurrence, as shown below.

[1] R. Pumpelly, *Proc. Am. Acad. Arts and Sciences*, XIII, 253.

The composition of the mottled type is indicated by the analyses of Table I, but each of the Minnesota samples is considerably altered. Nevertheless the calculated norm confirms the field conclusion that there was considerable variation in the proportion of minerals in the originals, and even some variety in the composition of some of the silicates.

Hackly diabase.—Microscopically these rocks are usually coarse grained but mineralogically similar to the mottled type. The texture is diabasic as distinct from ophitic, though intermediate textures are not rare. Many of the flows have well-defined amygdaloidal zones. Pumpelly's study of the metasomatic development of secondary minerals has been checked, as far as material was available, and Minnesota furnishes one type which he did not find well developed—the laumontite rocks.

Olivine was found in sections from one flow of hackly rock in Minnesota. Pseudomorphs, clearly from olivine, were found in about half the sections of this type; but some rocks, closely resembling these, showed no product or structure indicating that olivine had ever been present. The one Minnesota rock showing fresh olivine is so fresh compared with other flows of the region as to be hard to place with them, but there is no sign of mottling, and the texture is far from the typical ophitic. It gave Analysis 3, of Table II. The olivine is just beginning to alter along the borders and cracks to a chloritic mineral of strong pleochroism in brown and green. A little chlorite appears in other parts of the rock, but no room is left for any glass or its alteration products. This occurrence may well be substituted, in general discussions of the Keweenawan, for the type locality given in Michigan, No. 87 of Marvine's Eagle River section. However, it is not suggested that all hackly diabases were olivinitic. Olivine is present in this freshest sample, and its presence or absence is not a good point to use as a type characteristic. The pseudomorphs after olivine vary as before, and the development of magnetite and hematite along the cracks gives the pseudomorph the appearance of the high relief of olivine, in fully half the sections examined. Some of the pseudomorphs give a uniaxial figure, as recorded by Pumpelly.

In the fresh flow of the Snake River series, labradorite is the feldspar, but in the more altered samples very few crystals are fresh

enough to show twinning bands. In these the extinction is wavy and angles are low. Both oligoclase and orthoclase are probable.

Magnetite is seen in all sections and apatite in only one.

Alteration in most cases has proceeded even farther than in the mottled rocks, and resulted in a pseudo-amygdaloid—a botchy mass of secondary minerals. The original texture is revealed by some pseudomorphs, one of the most peculiar being a nearly opaque yellowish-green earth with the form of plagioclase. However, the pseudo-amygdules are quite abundant, developing from any spot as a nucleus, and expanding as they replace the surroundings with a new layer. Chlorite is the commonest material, varying from colorless to dark blue-green, or yellow, or brown, or gray, and usually spherulitic. In similar position in other rocks are calcite, quartz, epidote, actinolite, and a dusty red mineral of very feeble birefringence, which may be laumontite or some other zeolite. Regarding the development of most of these, reference must be had to Pumpelly's paper, but some new work is here offered regarding the laumontite rocks. There is an extensive development of this mineral in some amygdaloidal and vein cavities on Snake River in Minnesota. Its properties are given below with those of other amygdules. Beginning at Kettle River and extending twenty-five miles northeast, is a series of outcrops of a red pseudo-amygdaloid, associated with which are real amygdaloids with red laumontite. The red material of the pseudo-amygdules appears to be similar to that of the amygdules, but the rocks are badly softened and microscopic examination is not very satisfactory. A specific gravity separation of the rock-constituents yielded rather mixed material, the lightest fraction being strongest red in color. Chemical tests of the two lightest fractions show that there is an approach to laumontite (Analyses 4 and 5, Table VI), and there is no doubt that this mineral has developed in the rock-matrix as well as in the cavities. Pumpelly suggests the possibility, and thinks it an early product in the alteration. Its associates here are badly altered; only augite, of the original, is still recognizable in the mass, which affords clear evidence of its original texture.

An entirely distinct line of chemical work has given a hint of the history of some of the rocks. This is the composition of the product

of alteration of laumontite. Where excellent crystals of laumontite are found on Snake River, some perfect pseudomorphs were found with an entire change in certain constituents. Lime is lacking in the secondary mineral and potassium is prominent. In several parts of the area amygdules were found of similar character to this pseudomorph, and an analysis shows the chemical constituents to be similar. This development of a potassium mineral may not be a conclusive proof of the former presence of laumontite, but adds probability to the idea. In other places and other rocks, the potassium minerals found have very different characters. Further, on Upper Tamarack Creek this same mineral is largely developed with chlorite in a pseudo-amygdaloid, which may be a late derivative of the laumontite pseudo-amygdaloid. Analyses of these minerals are given in Table VI, but of the rocks in Table II.

TABLE II

ANALYSES OF HACKLY FRACTURING DIABASES

1. Taylors Falls, Minn. Rather fine grained. C. A. Taylor, student analyst.
2. Crooked Creek, Pine Co., Minn. C. Tronson, student analyst.
3. Pine City, Minn. Coarse and fresh. F. F. Grout, analyst.
4. 5. 6. Altered hackly diabase, forming a belt of laumontite pseudo-amygdaloidal outcrops, across the area of Keweenawan in Minnesota. F. F. Grout, analyst.

	1	2	3	4	5	6
SiO_2	48.68	53.20	48.27	42.35	47.22	47.54
Al_2O_3	19.29	15.83	16.29	17.24	17.17	17.40
Fe_2O_3	4.07	3.39	4.55	9.90	10.21	9.21
FeO	8.31	6.79	10.09	2.69	2.47	2.71
MgO	5.52	5.44	4.94	7.01	5.00	5.14
CaO	7.78	6.95	8.42	7.47	6.58	6.40
Na_2O	3.40	3.73	2.14	0.93	2.70	2.61
K_2O	1.16	1.34	0.77	1.48	2.15	1.80
H_2O-	0.10	0.63	0.64	1.57	0.54	0.73
H_2O+	0.16	1.44	1.67	7.13	3.73	4.38
TiO_2	1.70	1.35	2.46	1.84	1.96	1.79
CO_2	....	....	0.05	0.10	none	0.15
P_2O_5	0.05	....	0.14	0.14	0.15	0.06
S	....	....	0.04	none	none	0.04
MnO	....	0.15	0.17	0.15	0.12	0.11
BaO	....	....	0.04	0.01	0.03	0.02
Cr_2O_3	....	....	none	0.01	0.02	0.02
	100.31	100.24	100.71*	100.02	100.05	100.11
Specific gravity	....	....	2.986	2.695	2.821	2.778
	Hessose	Andose	Auvergnose	....	....	....

* CuO=0.03.

Conchoidally fracturing diabase.—This fracture appears only in the base of most flows, but throughout the whole mass in a few flows. The augite in these is less prominent and in small grains. The feldspar, also fine, is labradorite, oligoclase, or even orthoclase when recognizable. Olivine has not been recorded, but A. C. Lane concludes from the form of some secondary minerals, that they replace olivine. The composition indicates that olivine might develop, but, as in the previous types, it is best to assume its presence in some, but not all, of the rocks of this field type.

TABLE III

ANALYSES OF CONCHOIDALLY FRACTURING DIABASES

1. Type locality, Bed 65, Eagle River section, Keweenaw Point, Mich. George Steiger, analyst. *Journal of Geology*, XVI, 765.

2. Crooked Creek, Pine Co., Minn. Average material. F. F. Grout, analyst.

3. Tamarack Creek, Pine Co., Minn. Altered, but hard. F. F. Grout, analyst

4. Mouth of Kettle River. Altered to red clay. Partial analysis by F. F. Grout.

	1	2	3	4
SiO_2	50.07	53.16	65.00	43.35
Al_2O_3	12.63	15.12	14.01	20.42
Fe_2O_3	3.84	5.05	6.42	13.57
FeO	10.30	6.75	0.44	
MgO	5.23	4.76	2.83	5.17
CaO	6.55	5.74	0.85	0.27
Na_2O	3.53	2.38	1.82	0.35
K_2O	1.00	1.54	5.42	5.46
H_2O-	0.86	0.38	0.26	4.24
H_2O+	1.16	1.02	1.03	5.54
TiO_2	2.50	1.68	0.63	0.92
CO_2	none	0.05	0.07	....
P_2O_5	0.22	0.03	0.07	....
S	none	0.04	none	....
MnO	0.42	0.17	0.10	....
BaO	0.02	0.02	0.06	....
	100.03	99.75*	99.07	99.29
Specific gravity	.....	2.882	2.630	....
	Camptonose	Bandose	Nameless Hispanare	....

* CuO=0.02.

Alteration giving hematite is probably responsible for the red color of many outcrops. Sections reveal the fine-grained pseudomorphs after plagioclase, in a ground-mass, usually darkened by hematite, especially where it seems probable an augite area existed.

A large part of the ground-mass is now orthoclase in one or two sections examined, but many other minerals are associated: quartz, calcite, chlorite, etc.

Porphyritic variations.—In Minnesota, phenocrysts from one-half to two inches long are developed in the conchoidal and hackly fracturing types at several localities. At Taylors Falls they are red and elsewhere usually gray. The fresh samples are labradorite, but alteration had the same effects on these large crystals that were revealed in the smaller ones. As the grain becomes dusty and granular, extinction becomes wavy, twinning bands disappear, and if there is an aggregate extinction the angle is low. A hard rock of this type can be followed along the strike for some miles on Kettle River. Two samples from widely separated points differ from each other so little that only the average is given in Table IV. The extreme was a variation from 6.05 to 6.89 per cent of lime. The phenocrysts have not affected the composition to make it differ much from non-porphyritic types.

Glasses.—A few inches at the base of each flow is commonly of the appearance of devitrified glass, and the immediate region of the amygdules at the tops of flows is similar. The alteration is advanced, though the crystallization is never very coarse. The conchoidal fracture remains, and in plain light the sections reveal microlites in a translucent field, and a few show flow structures.

Amygdaloidal textures.—Most of the flows have an upper zone, not sharply distinct from the main body, but characterized by increasing numbers of cavities, around which the rock is more glassy than elsewhere. Such porous glass, chemically unstable and physically weak, and affording good channels for water-circulation, now contains such a variety of secondary minerals that it seems hard at first sight to assign them all to the same rock for origin. Some cavities are now open—probably from recent leaching; some are filled with a single mineral; some contain three or four minerals in complex relation to each other. The series of minerals in order of formation has been generalized in the Michigan reports, and is essentially correct in this area. Table IV includes two analyses of Minnesota amygdaloids, but they are not in this particular Keweenawan area.

TABLE IV

ANALYSES OF AMYGDALOIDAL AND PORPHYRITIC ROCKS

1. Porphyritic diabase, Kettle River, east of Hinckley, Minn. Average of two samples, some miles distant. F. F. Grout, analyst.

2. Thomsonite-bearing rock, Good Harbor Bay, Lake Superior. C. F. Sidener, analyst.

3. Similar rock, decomposed, nearer Grand Marais, Lake Superior. C. F. Sidener, analyst.

	1	2	3
SiO_2	50.48	46.80	45.37
Al_2O_3	16.33	15.21	18.21
Fe_2O_3	5.99	13.13	1.22
FeO	7.10		
MgO	4.08	8.13	6.98
CaO	6.47	11.11	11.49
Na_2O	2.44	1.05	0.84
K_2O	1.39	0.01	0.02
H_2O-	0.46	....	....
H_2O+	2.70	2.79	4.66
TiO_2	2.15	....	....
CO_2	0.01	....	....
P_2O_5	0.21	....	....
S	0.01	....	....
CuO	0.02	....	....
MnO	0.16	....	....
BaO	0.04	....	....
	100.04	99.13	99.77
Specific gravity ...	2.886	.....	.....
	Bandose	Auvergnose	.....

Amygdules and other secondary rock minerals.—Chlorite is probably the most important mineral of this group, forming amygdules, pseudo-amygdules, and pseudomorphs after glass, olivine, augite, and even plagioclase, with prehnite as an intermediate product. The similarity of constituents of this green earth and augite suggests that much of it originated from that mineral, and this idea is confirmed by the absence of much chlorite in the rocks low in augite. The variety of occurrence, however, as well as some small variations in optical properties, indicates several methods of formation and a variable composition. An early test of composition, by McFarlane of the Canadian Geological Survey,[1] by fractional solution in nitric acid and alkali gave a solution indicating the composition of delessite.

[1] Canadian Geol. Survey, *Report of Progress*, 1863–66.

Pumpelly had an analysis made with similar results. Both samples represented pseudo-amygdules, and the results have been widely accepted, though it seems possible some other constituent may have been attacked with McFarlane's chlorite. Dr. Berkey[1] found the chlorite amygdules of Grand Marais on the north shore of Lake Superior to be strigovite. Three of the samples now tested seem to be much like delessite and the fourth does not seem to be a definite chlorite. The analyses, though similar to those given by Dana, are quite different from earlier analyses of Keweenawan material. Those

TABLE V

ANALYSES OF CHLORITE AND "GREEN EARTH"

1. Chlorite, silky amygdules, Pine City, Minn. F. F. Grout, analyst.
2. Chlorite pseudo-amygdules, Upper Tamarack Creek, Minn. F. F. Grout, analyst.
3. Green earth of slickensides, Crooked Creek, Minn. F. F. Grout, analyst.
4. Green mineral from rock analyzed, Number 3, Table IV. C. F. Sidener, analyst.

	1	2	3	4
SiO_2	31.84	31.87	44.60	39.00
Al_2O_3	18.32	17.58	6.93	8.41
Fe_2O_3	2.59	7.63	9.59	10.69
FeO	13.80	8.67	3.94	
MgO	20.64	20.81	19.98	19.64
CaO	none	trace	0.74	3.59
Na_2O	trace	none	0.61	0.29
K_2O	trace	0.92	0.15	none
H_2O-	1.80	0.47	8.00*	....
H_2O+	10.40	11.63	5.00	17.07
CO_2	0.13	....	0.13	....
TiO_2	....	0.15	0.06	....
	99.52	99.73	99.73	98.69
Specific gravity	2.739	2.777	2.500	.....

* The moisture lost on drying at 100°, though great, was almost entirely regained after exposure to ordinary air.

were low in magnesia and high in alumina and iron oxides. The high ferric oxide which has been mentioned in connection with reduction of copper is less prominent in these new analyses. The chlorite has a hardness of about 2, and the color varies—usually green and light enough so that sections are very faintly colored. The structure

[1] C. P. Berkey, Minn. Geol. and Nat. Hist. Survey, *Ann. Report 23*, 194.

is usually radial, but in some, confused and very fine grained; double refraction is very slight and still notably variable.

Probably second in importance as an alteration product in these rocks are laumontite and related minerals. Their occurrence is mentioned above and it is now time to discuss the evidence of the relation of laumontite to an aggregate of quite different composition. The laumontite crystals, occurring on Snake River in greatest abundance, are red in color and usually form radiating groups up to two inches across. Terminal faces have developed on distinct prisms up to a quarter of an inch in thickness. The termination is the common laumontite form, classed as a dome (201) by Dana. The angle from prism to this dome varied quite widely in the crystals measured, but apparently this was due to the enlarging prism in the radiating group. Several measurements, by both hand and reflection goniometers, lay very close to the correct figure 113° 30′ and the rest varied within 5 degrees below that value, with no point more prominent than the rest. A trace of the pinacoid face could be seen on a few crystals. The prismatic cleavage is prominent, especially after the mineral has stood a time in a dry warm room. The blowpipe and physical characters clearly identified it.

Thin sections indicate hematite as coloring matter rendering the section dusty, but other alteration products contributed to this effect. Extinction was often wavy, and inclusions of different orientation crossed some grains in such a way as to remind one of microperthite. Such was the material of Sample 2, Table VI.

Light-green pseudomorphs formed from this red mineral. They preserved the angles of the original and showed the same development and imperfections. In a few illustrative specimens, the red center of laumontite is visible in broken green prisms. The cleavage cracks of laumontite show as light or more transparent lines in the pseudomorph. At this type locality, the chief chemical change is the replacement of lime and some water, by potash and magnesia. No formula is yet suggested for the mineral, however, because of the variation in similar material from other localities. It has a hardness of 3; specific gravity of 2.7; fusibility of 3; soapy feel; is an aggregate of grains, none of which was over 0.01 mm. in length; is anisotropic and has medium birefringence. Hydrochloric acid dissolves very little, and

TABLE VI

ANALYSES OF LAUMONTITE AND RELATED PRODUCTS

1. Light-pink laumontite, Pine City, Minn. F. F. Grout, analyst.
2. Dark-red laumontite, Pine City, Minn. F. F. Grout, analyst.
3. Dark-red laumontite, Kettle River, Minn. F. F. Grout, analyst.
4. Lightest fraction of red pseudo-amygdaloid, Crooked Creek, Minn. This is not a clean separation from feldspar, as shown by the next sample. F. F. Grout, analyst.
5. Next to the lightest fraction of the foregoing sample, No. 4. F. F. Grout, analyst.
6. Green pseudomorph after laumontite like sample No. 2. F. F. Grout, analyst.
7. Appeared to be bleached and further altered from sample No. 6. F. F. Grout, analyst.
8. Amygdules of similar appearance, Upper Tamarack Creek, Minn. F. F. Grout, analyst.
9. Pseudo-amygdules of similar appearance, associated with chlorite and hematite, Upper Tamarack Creek, Minn. F. F. Grout, analyst.

	1	2	3	4	5	6	7	8	9
SiO_2	51.34	49.66	49.44	48.85	53.58	53.73	53.02	62.78	48.80
Al_2O_3	22.48	21.15	20.62	25.01	26.16	15.08	20.55	15.52	19.63
Fe_2O_3	0.55	1.32	2.86	2.19		4.24	1.94	2.06	8.87
FeO	0.15	0.21	trace	trace		2.36	1.36	0.20	
MgO	0.97	1.44	1.29	1.73	1.67	9.12	7.31	3.19	7.50
CaO	10.68	9.16	9.46	6.84	5.56	0.08	0.08	none	trace
Na_2O	1.23	1.49	0.60	2.36	3.90	0.38	0.72	none	0.30
K_2O	0.40	1.38	1.66	2.21	3.16	8.02	6.20	5.82	5.98
H_2O-	1.66	2.90	2.40	2.00	....	1.02	1.82	6.23	1.74
H_2O+	10.14	10.80	11.97	9.34	....	5.55	5.36	4.50	6.30
CO_2	0.10	0.12	....	....	....	....	....	....	....
TiO_2	....	....	0.18	0.10	....	0.03	trace	0.06	0.77
	99.70	99.63	100.48	100.63	Incomplete	99.61	98.36*	100.36	99.89
Specific gravity	2.353	2.315	2.381	less than 2.580	2.581	2.750	2.677	2.581	....

* Two sets of duplicate analyses yielded consistently low summation. The alkali determination showed the poorest agreement; and the figure reported is that from the two highest results which were in close agreement. Sulphur, and carbonic acid are not present in amounts sufficient to change the total much.

yields no jelly as laumontite does. By thorough treatment with this acid and alkali, only 25 per cent is extracted and the extract resembles the original except in having more iron and none of the sodium and potassium. However, the addition of sulphuric acid, in the above treatment, makes decomposition complete. As the orthoclase of this same district gives only 3 per cent to this treatment, it seems certain

that this material is not a mixture of orthoclase and another mineral. No other mixture seems to fit the case and although the analyses show considerable variation it is quite certain that we are dealing with material not hitherto described. At least, it is a new alteration product for laumontite. It is here proposed that the new mineral be called *pseudo-laumontite*. Chemically it is unique in combining potassium and magnesium in a silicate. The rock-analysis No. 5, of Table I, resembles the analyses of pseudo-laumontite closely enough to be of interest in this connection.

TABLE VII

ANALYSES OF MISCELLANEOUS AMYGDULES

1. Orthoclase, fine-grained, salmon-pink tufts lining cavities, T.39N., R.21W., Pine City, Minn. F. F. Grout, analyst.

2. Analcite, red and white mottled crystals, associated with either laumontite or orthoclase, Pine City, Minn. F. F. Grout, analyst.

3. Prehnite, radiating groups in a light-green vein-filling, T.41N., R.20W., Kettle River, near Hinckley, Minn. F. F. Grout, analyst.

4. Datolite, enamel-like bunches, associated with chlorite in cavities, Pine City Minn. F. F. Grout, analyst.

5. Chalcedony, Crooked Creek, Pine Co., Minn. F. F. Grout, analyst.

	1	2	3	4	5
SiO_2	61.69	55.76	45.31	36.50	97.85*
Al_2O_3	19.46	23.24	20.60	trace	0.18
Fe_2O_3	0.76	0.53	5.45	3.58	0.46
FeO	0.93	0.40	trace	trace	
MgO	0.52	0.55	0.63	1.25	0.17
CaO	trace	trace	23.66	33.28	0.30
Na_2O	0.20	11.79	0.31	none	p.n.d.
K_2O	15.00	0.07	0.19	0.10	p.n.d.
H_2O-	0.10	0.10	0.16	0.16	none
H_2O+	0.97	8.06	4.40	5.95	1.00
CO_2	0.15	0.15	....	0.20	none
TiO_2	0.10	trace	....	0.10	0.04
B_2O_3	....	....	....	18.88*	....
	99.88	100.65	100.71	100.00*	100.00*
Specific gravity	2.615	2.283	2.896	2.951	2.618

* The percentage of silica in chalcedony and of boric acid in datolite are found "by difference." The difficult method of estimating boric acid gave the analyst 17.36 per cent B_2O_3 instead of 18.88. Material was exhausted before it was satisfactorily checked.

Several other minerals have been tested, chiefly by analysis, to estimate their purity. Analcite yielded measurable crystals of the common form. All of the mineral occurrences recorded with the

analyses are new occurrences. As datolite is new to the state except in the drift, it is worthy of record that it has another occurrence, on Crooked Creek. Record of metallic copper from many points might be made, but the mineral needs no analysis, except for silver, which was not found.

THE CHEMICAL CLASSIFICATION.[1]—Grouping the twelve new analyses of rocks that show little alteration (less than 3 per cent combined water) with five earlier results which seem to be good, the chemical character of the diabases may be summarized. More results fall in the subrang *Hessose*, than any other, and this is a persodic, docalcic, perfelic dosalane. The similar groups Bandose

TABLE VIII

ANALYSES OF BASIC DIABASE DIKES OF MINNESOTA

1. Diabase dike, Stearns Co., Minn. B. F. Noehl, student analyst.
2. Olivine diabase dike, Carlton Co., Minn. W. H. Truesdell, student analyst.
3. Diabase dike, Stearns Co., Minn. Average of two analyses, side and center of 14-foot dike, essentially the same. F. F. Grout, analyst.
4. Diabase with phenocrysts of quartz and feldspar in a 5-foot dike. F. F. Grout, analyst.

	1	2	3	4
SiO_2	50.51	49.34	48.45	52.91
Al_2O_3	15.30	13.03	12.70	17.56
Fe_2O_3	1.79	2.50	2.00	0.00
FeO	8.14	13.74	13.24	8.61
MgO	5.94	3.64	4.39	4.90
CaO	9.04	7.40	8.50	7.55
Na_2O	5.18	4.55	3.94	3.72
K_2O	2.00	1.57	1.22	1.70
H_2O-	0.00	0.24	0.00	0.00
H_2O+	1.43	0.69	1.58	1.57
CO_2	....	0.96−	0.00	....
TiO_2	2.80	3.16	3.17	0.92
ZrO_2	....	0.04	....	....
P_2O_5	....	0.15	0.72	0.20
MnO	0.51	0.51	0.17	0.11
S	....	0.12	....	....
BaO	....	0.03	....	....
Cr_2O_3	....	0.02	0.10	0.20
	102.64	101.64	100.18	99.95
Specific gravity	....	....	2.90	2.840
	Limburgose	Kilauose	Auvergnose	Hessose

[1] *Journal of Geology*, X, 555.

and Auvergnose are well represented. Of the 17 analyses, 17 are persodic, 12 are docalcic, 12 are perfelic, 10 are dosalic. The variation of the others is not uniform.

Such relationships in composition may be taken as evidence of origin from a common magma, and the differences that exist in the unaltered rocks are therefore to be attributed to some process of differentiation. Alteration is too great for accurate discussion of the subject. Mr. Lane has raised the question of differentiation in a single flow.[1] His opportunity to examine extensive drill cores, gave him results that are beyond comparison with any now to be added from a rapid field survey. He found some changes which appeared to be due to an early separation of oligoclase which was lighter than the basic magma, and rose, affecting both composition and texture. Analyses are offered in confirmation, but the high degree of alteration, indicated by 5 per cent water and 1 per cent carbonic acid, makes the chemical evidence of much less value than the microscopic work. Mr. Lane does not suggest that such action was common in the

TABLE IX

ANALYSES OF BASIC LACCOLITHS OF MINNESOTA

1. Gabbro, Richmond, Minn. E. M. Pennock, analyst.
2. Gabbro, Little Falls, Minn. Miss Lillian Nye, student analyst.
3. Gabbro, Duluth, Minn. Several student analysts obtained results, from 102 to 103 per cent. The lowest is by G. H. Stone, given below.

	1	2	3
SiO_2	52.34	44.16	49.42
Al_2O_3	14.17	14.89	24.47
Fe_2O_3	2.40	1.19	3.13
FeO	10.78	6.83	6.13
MgO	3.51	14.40	1.00
CaO	7.25−	13.01	8.45
Na_2O	3.73	1.92	4.98
K_2O	2.37	0.97	1.15
H_2O-	0.18	0.05	0.06
H_2O+	0.43	0.89	0.55
TiO_2	2.21	0.89	1.87
P_2O_5	0.80−	....	0.04
MnO	0.09	trace	0.11
S	0.14+	....	0.11
	100.40	99.30	101.48
	Camptonose	Portugare	Andose

[1] A. C. Lane, *Michigan Geol. Survey*, VI, 215.

Keweenawan, and no such case has been noted in Minnesota. Slight peculiarities were not rare; as, for example, the gneissic appearance, mentioned by Professor Hall regarding a Pine City exposure. This was prominent in the lower twenty-five feet of a thick hackly flow.[1]

In Michigan some diabase dikes in rocks near the lavas have been compared with the lavas, as an indication of their relationship. A similar comparison may be instituted here for Minnesota, and extended to include other occurrences of basic rocks in the central and northeastern part of the state. Earlier analyses reported by Streng, Winchell, and Irving are included in the tabular comparison, but analyses are not quoted.

TABLE X

CHEMICAL CLASSIFICATION BY LOCALITY AND FORM

	Labradorose	Dacose	Varingose	Tonalose	Bandose	Shoshonose	Andose	Hessose	Vealose	Kilauose	Camptonose	Ornose	Auvergnose	Limburgose	Desodic / Dacitic / Portugare
Minnesota flows.....	−	−	+	+	+	−	+	+	−	−	+	−	+	−	−
Michigan flows.....	−	−	−	+	+	−	+	+	−	−	+	+	+	−	−
Minnesota dikes.....	−	−	−	−	−	+	−	+	−	+	−	−	+	+	−
Michigan dikes.....	−	−	−	−	−	−	−	+	+	−	−	−	+	−	−
Duluth gabbro.....	+	−	−	−	−	−	+	+	−	−	−	−	−	−	−
Stearns Co. gabbro....	−	+	−	−	−	−	+	+	−	−	+	−	+	−	±

TABLE XI

TYPES OF DIABASE CHEMICALLY CLASSIFIED

	Hispanare	Tonalose	Bandose	Shoshonose	Andose	Hessose	Kilauose	Camptonose	Auvergnose
Mottled type	−	−	−	−	−	+	−	−	−
Hackly type.....	−	+	+	−	+	+	−	+	+
Conchoidal type ..	+	−	+	−	−	−	−	−	−
Dike rock.....	−	−	−	+	−	+	+	−	+

[1] C. W. Hall, *Bull. Geol. Soc. Am.*, XII, 313.

DIABASE AND GRANOPHYRE OF THE GOWGANDA LAKE DISTRICT, ONTARIO

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INTRODUCTION

The rich silver deposits of Nipissing and Temiskaming districts of Ontario are believed to be genetically connected with intrusive diabases. Chiefly on this account, these diabases have received considerable attention from many Canadian geologists.

During the summer of 1909 special opportunity for studying these rocks was afforded by the Ontario Bureau of Mines, to the writer, while working in the vicinity of Gowganda Lake.

The results of this study form the basis of this paper.

GENERAL GEOLOGIC RELATIONS

A brief résumé of the geologic history of the Gowganda district[1] will be given in order that general relationships may be well understood.

The oldest rocks consist of a complex of chloritic and hornblendic schists (altered basic volcanics), cut by quartz porphyries; together with a minor quantity of jasper-iron formation and its associated schists. This schist series (Keewatin) was subjected to intense folding and its schistose character induced before the intrusion of the great granite batholiths which in numerous places in the area are seen cutting the series. This complex (Archaean) suffered a long period of erosion before the deposition of the sedimentary series now lying upon it. The lower series is made up of conglomerates, quartzites, and slates of varying thickness. This in turn suffered erosion, but apparently little disturbance, before the deposition of the conglomerate-arkose-quartzite series lying upon it. These series have been called Lower and Middle Huronian respectively. Into

[1] See also forthcoming report and map by A. G. Burrows, Ontario Bureau of Mines, 1910.

all the foregoing series are intruded sills and dikes of diabase, the sill-like form being generally assumed in the sedimentaries. The succession here noted is essentially that found in all the Huronian areas of northern Ontario which have received careful study. The diabase is of remarkably uniform character in widely separated districts.

Throughout the Gowganda area, with few local exceptions, the sedimentaries with their sills have been little disturbed. They lie in monoclinal blocks with average dips of about 12 degrees to the east.

NORMAL SILL DIABASE

The normal diabase of the sills is, when unaltered, a dark-gray, medium-grained, holocrystalline rock, of which the chief constituents are plagioclase and pyroxene with a very little quartz, micropegmatite, biotite, apatite, and black iron ore.

The plagioclase, amounting to about 60 per cent of the total, occurs in stout laths with average length of about 0.5 mm., idiomorphic against pyroxene. Extinction angles place it as medium labradorite, $Ab_{35}An_{65}$. Sometimes zonal growth is shown and in favorable cases the outer zone could be determined as acid labradorite, $Ab_{45}An_{55}$. The plagioclase is generally somewhat altered, minute scales of white mica being the chief product of alteration. The pyroxene is in irregular grains between the feldspar laths. There appear to be two varieties. Normal augite with the usual high interference colors, high extinction angle, and frequent twinning is the more common. The average size of individuals is about 0.5 mm. In lesser amount occur grains of average diameter 2.0 mm. without twinning, showing nearly always parallel extinction, but in some sections as high as 10 degrees inclination. The maximum interference color is a pale yellow of the first order; the optical character is positive as in the augite; a faint pleochroism is shown. Bayley describes a mineral in his Pigeon Point rocks[1] which seems to be identical. The relation of this pyroxene to the feldspar is the same as that of the augite, but the large size of its grains suggests that it *began* to crystallize sooner. The pyroxene is probably enstatite. The appearance of slightly oblique extinction in rare cases is to be explained in its

[1] *Bull. 109*, U.S.G.S., 36, 45.

wide axial angle. The slide presents no difference whatever from the diabase of the Cobalt area. Biotite, black iron ores, and apatite are the accessory minerals. Small areas of micropegmatite of quartz and an indeterminate feldspar are always present.

GABBRO

In places the diabase has moderately coarse phases with augite in stout prisms showing one perfect cleavage face, the diallagic parting, which determines the fracturing of the rock. The cleavage face is nearly always bent, sometimes into a considerable arc. This bending is a constant character of the augite of the coarse phase from widely separated points. Under the microscope this phase shows a nearly simultaneous crystallization of augite and plagioclase, the feldspar in broad areas generally inclosing the augite.

The feldspar is an acid labradorite, $Ab_{45}An_{55}$, approximately that of the outer zones of the crystals of the normal diabase. Some zonal growth was shown in a few examples, the outer zones being slightly more acid.

The pyroxene is augite throughout, with cleavage parallel to 100 and a lamellar structure parallel to the base. Enstatite is absent. The augite has often gone over, partly, to uralite. Both augite and plagioclase are in stout prisms of about 3 mm. average length. There is no evidence of granulation of any of the constituents, so the bending of the augite must be attributed to disturbance during crystallization. A little iron ore occurs, and moderately coarse micropegmatite interstices in small amount. The feldspar of these could not be determined. Where micropegmatite is in contact with iron ore and augite, secondary biotite has sometimes been built. The rock is a gabbro, near augite diorite.

No definite relation of the gabbro to the sill boundaries could be made out. There is usually a gradual passage from diabase to gabbro, but in some cases small dikelike masses of the gabbro were found in diabase. The gabbro probably represents the more slowly crystallized, slightly more acid parts of the sills. This phase is well developed in the area west of Logan Lake. In places in this area the gabbro becomes very coarse, with pyroxenes up to three inches in

length, often showing alignment, indicating motion in the mass during crystallization.

TABLE I

SiO_2 ..... 50.12				
Al_2O_3 ..... 15.70				
Fe_2O_3 ..... 1.42	Norm.			
FeO 6.89	Or 6.12	F=54.82.	Sal.=56.24	
MgO 9.50	Ab 22.01			
	An 26.69			
CaO 11.30	Nep 1.42	L= 1.42		
Na_2O 2.91	Di 23.73	P=23.73		
K_2O 1.07	Ol 16.22	O=16.22		Fem.=43.34
H_2O+ 1.03	Mt 2.09	M		
	Il 1.06			
H_2O- 0.21	Pyr 0.24	A		
TiO_2 ..... 0.55	III, 5, 4, 3			
S 0.14	Auvergnose			
100.84				

I. NORMAL DIABASE, O'BRIEN MINE, COBALT. N. L. BOWEN, ANALYST

DIKES

In the Davidson Lake sill, which will be described later at greater length, a well-defined dike of fine-grained diabase was found cutting the normal sill rock. Slender laths of plagioclase averaging 0.3 mm. in length are set in a matrix of augite. The plagioclase is very fresh and ranges from acid labradorite to acid bytownite. Augite fills the interspaces and is sometimes altered to a felt of needles of low birefringence with skeletons of iron ore, like the alteration products described by Pirsson in West Rock diabase.[1] Iron ore forms about 15 per cent of the rock. There is a little pyrite, but at least some of this has filtered in along tiny seams. No quartz could be found.

Dikes are exceedingly numerous in the Archaean, often up to 250 feet in width and of very uniform character. With the exception of the chilled margin the dikes are in most cases composed entirely of dark-gray, rather fine-grained, normal diabase. Sometimes, however, large phenocrysts of feldspar up to 2 inches in length, often with a flow arrangement parallel to the walls, stand out on the weathered

[1] Diller, *Educational Series of Rock Specimens*, 271–72.

surfaces. One especially fine example lies east of Davidson Lake where a dike about 200 feet wide, cutting the Archaean complex, shows phenocrysts from wall to wall. Only one dike, definitely determinable as such, was seen in the sedimentaries and this was near the basement Archaean. This was of the porphyritic type. The phenocrysts carefully determined in oriented sections are mainly a uniform andesine, $Ab_{55}An_{45}$. A narrow outer rim usually shows zonal growth with zones of labradorite, $Ab_{45}An_{55}$, and andesine alternating. In some cases the phenocrysts contain idiomorphic crystals of olivine near their outer edges.

The ground-mass consists of plagioclase, augite, olivine, apatite, and iron ores.

The plagioclase is mainly labradorite sometimes showing zonal growth, with acid andesine forming the outer zones. In a few cases the core is andesine with a zone of labradorite surrounding it and then again andesine as the outer layer.

The olivine is in small grains, usually very fresh. It is optically negative and therefore belongs to the iron-rich olivines. Most of it appears to have crystallized before the feldspar of the ground-mass. A brownish augite fills interspaces of the ground-mass between the feldspar laths in perfect ophitic structure. Apatite is unusually abundant, in very long needles, which penetrate all the constituents. No quartz or micropegmatite were found. Black iron ores are rather abundant.

GRANOPHYRE AND RELATED ROCKS

None of the dikes show evidence of differentiation as far as can be determined in the hand specimen. The sills, however, are not always entirely composed of the dark-gray diabase. In places we often see little pink spots, found to be areas of micropegmatite (quartz and albite). This material may increase in amount until it forms quite the whole of the rock, giving rise to "red rocks" or granophyres. Moreover pink aplitic veins are often numerous in the sills. To the development of these "red rocks" and their relations to the diabase and inclosing sediments attention will now be given.

DAVIDSON LAKE SILL

Close to the west shore of Davidson Lake is a sill about 50 feet thick cutting the arkoses of the Middle Huronian (Fig. 1).

Its western edge (the base) has a chilled margin against the sediments. The arkose has been bleached; otherwise there is no notable effect at the contact. As we approach the eastern edge (the top) we find "pink spots" appearing in the diabase. The actual contact could nowhere be found, but at one point the sill rock within a foot of the sediment was seen to consist entirely of a pink feldspathic

FIG. 1.—Ideal section at Davidson Lake. ark. = arkose; di. = diabase; gr. = Archaean granite.

variety. The microscope shows this rock to be made up of phenocrysts of acid plagioclase (albite to oligoclase-albite) in a groundmass of the same material with quartz and a small amount of augite and black iron oxide.

THE FOOT LAKE SILL

To the northwest of Foot Lake, diabase is found in contact with a narrow band of Lower Huronian slates (*A*, Fig. 2).

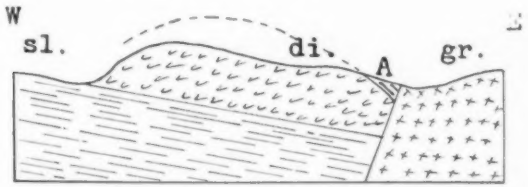

FIG. 2.—Ideal section of Foot Lake sill (laccolith). sl. = slate; di. = diabase; gr. = granite.

The slates near the contact normally greenish to pale reddish are changed in color to a deep purplish red. Under the microscope it is found that each lamina of sediment has been transformed to a mosaic of quartz and feldspar with a considerable proportion of chlorite and small grains of black and red iron ore. In the varying proportion of

chlorite and the varying "grain" of the mosaic the original lamination of the sediment is preserved. The feldspar is stained a deep red by tiny flakes of hematite. In a few individual grains albite twinning was discernible and the extinctions combined with the indices determined them as albite. Rarely small garnets are found.

It is typical adinole of diabase contacts believed to be produced by waters emanating from the diabase.

The intrusive becomes finer in grain as it approaches the sediment. For about three inches from the contact the diabase has a few "red spots" and these prove to be micrographic intergrowth of quartz and albite. The red color is seen to be due to little flakes of hematite in the feldspar. The plagioclase of the diabase proper has in large part gone over to sericite, and most of the augite to chlorite. Small pink garnets are an important constituent of this micropegmatite and sometimes amount to about 10 per cent of its bulk.

In places a zone of brecciated slate a few inches wide occurs along the contact. The "diabase" filling the spaces between fragments of slate is very rich in this pink micropegmatite (quartz and albite); is indeed sometimes composed almost entirely of it. Obviously the altered sediment has been influential in the production of this granophyric material (see Fig. 5).

About 100 yards south of the point just described, and on the same contact, the diabase has again these "red spots" near its contact and it passes rather abruptly into a reddish feldspathic rock about 5 feet thick. This is found under the microscope to consist of large phenocrystic individuals of albite in a ground-mass of quartz, albite, and chlorite. The quartz amounts to about 15 per cent and the chlorite to about 30 per cent, black iron ore about 5 per cent. A very few small garnets are scattered throughout the rock. The albite has again the tiny flakes of hematite, whence the red color. Small areas of very fine micropegmatite are found, showing the beginning of a granophyre structure. The rock has obviously the composition of adinole and passes quite gradually into the reddish-purple adinole which retains the structure of the original sediment. It is merely the more perfectly recrystallized adinole, closer to the intrusive. The granophyric material of special development in the diabase close to its contact has been introduced from the adinole at the time of its forma-

tion by some sort of "transfusion."[1] It has the same composition (albite and quartz, with some chlorite and garnets) as the adinole. In the diabase near this contact aplitic veins, consisting essentially of albite and quartz, are especially numerous.

LILY LAKE SILL

The diabase to the southwest of Lily Lake has often a high proportion of "red spots." On the north boundary of H.S. 646,[2] (*A*, Fig. 3) is found a variety which in the hand specimen would be termed a syenite. It is, in fact, composed almost entirely of the granophyric material which forms the "red spots." Under the microscope it shows phenocrysts of albite in a graphic intergrowth of quartz and feldspar, with a tendency to radial arrangement about the phenocrysts. The feldspar of the graphic growth is often in con-

FIG. 3.—Ideal section at Lily Lake. sl. = slate; di. = diabase

tinuous orientation with the phenocrysts. Sometimes the albite twinning lamellae pass from the phenocrysts into the feldspar of the micropegmatite without interruption. A very small proportion of the feldspar of the graphic material is a microperthite. Chlorite, apatite, iron ore, and calcite are present in small amount. The rock is a typical granophyre.

There is a small patch of thinly laminated graywacke slate within thirty feet of the outcrop of this granophyre. It evidently overlies the granophyre, but the two could not be found in contact. Some of the slate is altered by the intrusive into a rock with alternating dark greenish chloritic and reddish feldspathic laminae. Other parts of the slate are less altered and some apparently unaltered. Some chemical determinations made in samples of the altered slate will be given later.

[1] A. Harker, *Natural History of the Igneous Rocks* (1909), 304.

[2] See map by A. G. Burrows, Ontario Bureau of Mines, 1910.

THE LOST LAKE SILL

The best exposure of granophyre found lies along the west shore of Lost Lake (Fig. 4). In the hand specimen it would be termed a hornblende syenite. It lies at the top of a diabase sill which diamond drilling has shown to have a thickness of more than 500 feet, probably much more. Here a vertical thickness of about 30 feet of granophyre is exposed on the hillside overlooking the lake. Capping the hill is a thin veneer of nearly flat-lying sediments. It is difficult to draw an exact line of contact. Between what is unquestionably altered sediment, and granophyre is a layer about 1 foot thick of a purely feldspathic rock, red in color, and very similar to the granophyre. The microscope shows only feldspar (albite), with a little calcite and blotches of chlorite. The altered sediment close to this feldspathic

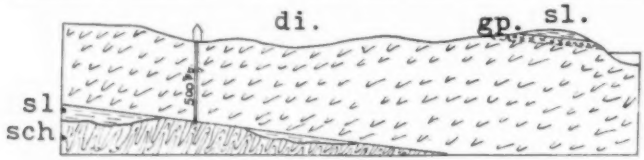

FIG. 4.—Ideal section at Lost Lake. sch. = Keewatin greenstone; sl. = slate; di. = diabase; gp. = granophyre.

layer has the granular appearance of a fine-grained indurated red arkose and under the microscope shows a mosaic of quartz and feldspar, some of which is determinable as albite. This gradually assumes a deep purplish-red color and in places passes into apparently unaltered slates. The whole change takes place within a distance of about twenty feet.

Going northward from the exposure just described there is a rather quick passage from granophyre, through diabase rich in granophyric material, to normal diabase, which is itself found in contact with little-altered slates. The granophyre is, then, not everywhere present at the upper contact of this sill, but for some reason is localized.

The granophyre itself is very similar to the Lily Lake rock. Albite phenocrysts are a little less abundant. A small part of the feldspar of the micropegmatite is microcline with, as before, some microperthite. The chlorite occurs in long blades probably secondary after hornblende. Calcite, apatite, and iron ores are again present.

TABLE II

	I	II	III	IV	V
SiO_2	62.54°	52.54	48.41	50.12	78.28
Al_2O_3	14.79	15.14	19.29	15.70	12.00
Fe_2O_3	...	0.85	1.33	1.42	....
FeO	8.49	10.73	8.27	6.89	1.19
MgO	2.08	5.22	4.70	9.50	0.37
CaO	1.49	6.92	4.93	11.30	0.29
Na_2O	6.27	5.46	5.92	2.91	6.89
K_2O	1.12	1.43	0.41	1.07	trace
H_2O	3.51	1.76	3.99	1.24	0.61
CO_2		....	2.41	....	....
TiO_2	....	1.00	0.88	0.55	0.34
	100.29	101.05	100.54	....	99.97

I. Lost Lake granophyre. Marked °, determined by N. L. Bowen, others by N. L. Turner.

II. Granophyric diabase, Pense Township. Analyst, N. L. Bowen.

III. Granophyric diabase, Bartlett property, Gowganda. Analyst, N. L. Bowen.

IV. Normal diabase, O'Brien mine, Cobalt. Analyst, N. L. Bowen.

V. Aplite vein in diabase, James Township. Analyst, N. L. Bowen.

TABLE III

	I	II	III	IV	V
SiO_2	....	62.54	60.70	75.43	79.43
Na_2O	5.12	6.27	9.33	5.72	4.73
K_2O	0.95	1.12	0.43	0.21	0.32

I. Lily Lake granophyre. Analyst, N. L. Bowen.

II. Lost Lake granophyre. Analyst, N. L. Bowen.

III. Albite rich layer at contact, Lost Lake. Analyst, N. L. Turner.

IV. Altered sediment near contact, Lost Lake. Analyst, N. L. Bowen.

V. Altered sediment near contact, Lost Lake. Analyst, N. L. Turner.

ORIGIN OF GRANOPHYRE

Summing up the evidence of the upper contacts of the sills, just described, we have at the Foot Lake sill, in one place, the special development of granophyric material in the diabase quite close to its contact with altered slate or adinole, the granophyre interstices having practically the same composition as the adinole and evidently derived from the latter by some process of transfusion. A little farther south where the action has been more intense we have a wider zone of adinole developed. Part of the adinole close to the diabase

has been to some extent recrystallized, giving the beginning of granophyric structure. The writer believes that in the case of the Lily Lake and Lost Lake sills the evidence points to a still more complete recrystallization of *part* of the adinole with the production of typical granophyre. In other words, some of the adinole was essentially in a state of aqueous fusion and crystallized as granophyre. The melt thus formed was, to a certain extent, free to diffuse into the diabase magma and gave rise to the abundant granophyric interstices near the granophyre.

If we inquire into the conditions of the formation of adinole from slates, we will find that wholesale introduction of albite, as such, is not necessary. Some magnesia, iron, and alumina are lost by the sediment. Silica has probably not been introduced, for the loss of the above-mentioned constituents suffices to increase the silica to the percentage in adinole. Finally potash, too, is lost and at the same time is replaced by soda.[1] Carbonate waters bearing a little soda could accomplish the work necessary. That such waters exist in basaltic magmas and have important effects during the late stages of crystallization is the conclusion of Bailey and Grabham in a late article.[2] If the conclusions of the present writer are correct, such waters, emanating from the diabase, have produced the adinole and the albite-rich granophyre here described. The waters supplied most of the soda and the sediment supplied alumina and silica. Calcite is an almost universal constituent of the aplite veins associated with the granophyres. It has in some cases apparently crystallized together with the aplite minerals.[3] This certainly points to the presence of carbonate waters.

It has been pointed out that magnesia, iron, alumina, and potash are the chief constituents carried away in the production of adinole. Presumably the waters carrying these would lose their solvent power at no great distance, due to fall in temperature, and they would be deposited. The small patch of altered slate at a little distance from the Lily Lake granophyre (see p. 665) may have been thus affected. The microscope shows that the most altered parts are rich in chlorite

[1] E. Kayser, *Zeit. der Deutsch. geol. Gesell.*, XXII (1870), 103 ff.

[2] *Geol. Mag.*, VI (1909), 256.

[3] A. E. Barlow, *Jour. Can. Min. Inst.*, XI (1908), 272.

(magnesia, iron, alumina, silicate) and analysis shows that the most altered parts are also richer in potash.

	Much Altered	Less Altered	Apparently Unaltered
SiO_2	54.77	58.48	61.54
CaO	0.65	1.08	0.84
Na_2O	4.85	4.81	4.73
K_2O	3.50	3.11	2.64

There is of course no check on original variation in the composition of the sediment, but the results accord so well with what would be expected, if the granophyre was formed as here imagined, that they are to be regarded as, in some degree, corroborative.

The partial analyses, Nos. IV and V, Table III, of the altered sediment (adinole) near the Lost Lake granophyre, together with its microscopic examination, show it to be an albite-quartz rock approximating the granophyre in composition. The nearly pure albite layer, No. III, Table III, between granophyre (recrystallized adinole) and adinole probably separated from the fluid granophyre. Albite is certainly in excess in the granophyre (note phenocrysts) and its separation toward the adinole would be especially favored by the composition of the latter.

That the granophyre "solution," formed as here imagined, was foreign to the diabase magma is indicated by the intense alteration of the constituents of the diabase near the granophyric interstices.[1]

The aplitic veins[2] (quartz and albite, often with calcite) which cut both granophyre and diabase were formed from the more aqueous residuum of the granophyre. They are especially numerous near a mass of granophyre. The extreme purity of their albite (note analysis No. V, Table II) points to their aqueous origin, as does also their calcite content. This aqueous residuum probably deposited also the valuable metallic content of the aplite veins and of the associated calcite veins. The association of gold with the similar soda-rich rocks of Alaska, California, and Ireland is worthy of note (see p. 671, below).

[1] See A. E. Barlow, *Jour. Can. Min. Inst.*, XI (1908), 271.

[2] N. L. Bowen, *Jour. Can. Min. Inst.*, XII (1909), 95–106.

The extent to which the comparatively simple relations, exhibited at the contacts described, would be obscured by reintrusion of the mixed magma to a higher level may well be imagined.

DISCUSSION

As opposed to the explanation of the origin of the granophyre here advanced, the explanation which would probably first suggest itself is that diabase and granophyre are normal differentiates from a common magma, influenced by gravity. This assumption would neglect the evidence of the Foot Lake contact. Here highly granophyric diabase has developed between the slate fragments of the contact breccia.

Some of the dikes which feed the sills have a width greater than 200 feet. Assuming a normal differentiation in the sills, it seems likely that it would take place in dikes so wide, giving enrichment in granophyric material toward the central portions. Evidence of this could nowhere be found.

The Foot Lake sill has a thickness of only 50 feet, yet it has the acid rock developed at its upper contact.

The theory here advanced also accounts logically for the passage of granophyre into adinole of approximately its own composition.

It has been stated that the diabase in all parts of the sills shows micropegmatite interstices. Possibly much of this material may have an origin entirely different from that of the red interstices close to the granophyre. It should, however, be remembered that the dikes are sometimes without micropegmatite.

The separation, which is here postulated, of soda-bearing carbonate waters from the magma is of course a sort of differentiation, but is not in itself sufficient to produce granophyre but only to contribute to its formation by inducing alteration of the *slaty* sediments.[1] A necessary conclusion seems to be that granophyre would not have been formed had the country rock of these intrusions been pure limestone or pure quartzite just as adinole is not produced in such cases.[2]

This conclusion suggests a test of the hypothesis here advanced in

[1] The importance of contact metamorphism in the genesis of igneous rock types has long been advocated by the French school of petrologists.—A. Michel-Levy, *Bull. Soc. Geol. Fr.*, 24 (1896), 123 ff.; also 25 (1897), 367.

[2] W. Hutchings, *Geol. Mag.*, II (1895), 122–63.

examining the association of albite-rich igneous rocks described in the literature.

In California[1] the soda-syenite famous for its association with the Mother Lode gold deposits occurs along the contact of basic igneous rocks with Mariposa slates. This syenite is in places an almost pure albite rock; at others it contains some quartz and muscovite.

In Alaska the Treadwell soda syenite[2] of the Treadwell mine cuts slate and is followed by gabbro.

In Ireland, at Croghan Kinshela, albite granite here associated with normal potash granite cuts Silurian slates.[3]

In the Isle of Man albite-rich dikes associated with diabase cut Silurian slates.[4]

The albite-rich keratophyres of Westphalia cut slates.[5]

Quartz keratophyres in Australia are associated with diorites and cut slates.[6]

A notable point concerning all of these is their small quantitative importance.

If we extend our search to rocks rich in plagioclase near albite, we find the same general association.

In the Marysville district of Montana a rock made up of quartz 40 per cent, oligoclase-albite 40 per cent, magnetite 10 per cent, muscovite 10 per cent, has been produced at the contact between gabbro and altered argillaceous sediment by a process of "hydrothermal alteration along the contact plane."[7]

Plumasite, an oligoclase-corundum rock, occurs in California as a dike cutting peridotites which in turn cut clay slates.[8] It has been considered genetically related to the albite syenites. The excess of alumina (corundum) in the plumasite is suggestive in relation to its genesis by interaction of the basic magma and clay slates.

[1] H. W. Turner and F. L. Ransome, *Folios 41, 43,* and *63,* U.S.G.S.

[2] G. F. Becker, *18th Ann. Rept.,* U.S.G.S., Part III (1896), 39 and 65; C. W. Wright, *Bull. 287,* U.S.G.S., 95.

[3] S. Haughton, *Q.J.G.S.* (1856), 268; W. J. Sollas, *Tr. R. Ir. Ac.,* XXIX (1891), 427.

[4] B. Hobson, *Q.J.G.S.* (1891), 432. [5] O. Mugge, *L.J.* (1893), B.B. VIII, 535.

[6] A. Howitt, *Geol. Survey Victoria,* IV (1877), 75–117.

[7] Barrel, *P.P. 57,* U.S.G.S., 48.

[8] A. C. Lawson, *Bull. Univ. of Cal.,* III, No. 8, p. 219.

At very many places in the British Isles granophyres associated with gabbro occur. Rosenbusch notes this general association.[1] At many of these places the granophyre is especially rich in plagioclase near albite and together with the gabbro is intruded into *slaty* sediments. The Carrock Fell[2] granophyre and the Buttermere and Ennerdale granophyre are perhaps the best-described examples. In the latter case it has been demonstrated that the associated Mecklin Wood dolerite has reacted with the sedimentaries.[3]

Near St. David's Head, Wales, *gabbroidal* sills cut Arenig *shales*. An oligoclase-rich rock has been produced near the contact by interaction with the sediment.[4] Granophyric interstices have also been produced near the sediment even where the contact-chilling effect is noticeable. It seems impossible to deny the influence of the sediment in the production of these granophyric interstices.

It would, of course, be quite unsafe to assume that the hydrothermal action here postulated was the dominant control in the development of the British granophyres mentioned. Some granophyres (micropegmatites) are believed by certain authors to have been produced by direct assimilation of sediments.[5] The result has been in these cases essentially a normal potash-rich granite. As pointed out before, assimilation of sediment has been noted in the case of some of the British rocks described, and this introduces new complications. It is rather their general tendency to richness in soda which indicates that hydrothermal action on the sediments may have had a part in their formation.

If albite-rich rocks were normal differentiates from a certain class of gabbroidal magma, they ought to be found in any association. The kind of "country rock" should make no difference. A search of the literature, summarized in the foregoing, seems to indicate that the kind of "country rock" does make a difference. It may be that argillaceous sediments are especially susceptible to the sodic waters;

[1] *Mik. Phys.*, II, 413.

[2] A. Harker, *Q.J.G.S.* (1895), 125; *ibid.* (1896), 320.

[3] R. H. Rastall, *Q.J.G.S.* (1906), 268.

[4] J. V. Elsden, *Q.J.G.S.* (1908), 275–76.

[5] W. S. Bayley, *Bull. 109*, U.S.G.S.; R. A. Daly, "Secondary Origin of Certain Granites," *A. J. Sc.* (4); A. P. Coleman, "The Sudbury Laccolithic Sheet," *J.G.*, XV, 773.

and this seems likely. Perhaps, also, water originally contained in the sediment and, in this class, in large amount, takes an important part in the transfer of material.

SUMMARY

1. The diabase of the Gowganda area occurs as sills and dikes cutting the older formations.

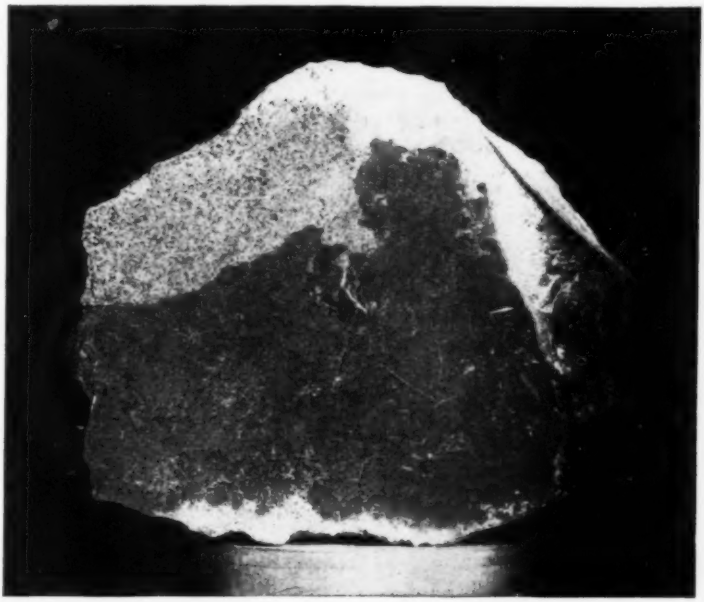

FIG. 5.—Photograph of polished specimen (natural size), showing light-colored granophyre-rich "diabase" against dark-colored, brecciated slate (Foot Lake).

2. The dike rocks are commonly porphyritic and olivine-bearing and never show distinct evidence of differentiation.

3. The sill rocks are never porphyritic; olivine is represented by the more silicic enstatite; granophyric interstices visible in the hand specimen as "red spots" sometimes occur.

4. A typical granophyre sometimes occurs at the upper contact.

5. The granophyre, like the granophyric interstices, is albite

rich and is transitional into albite-rich adinole, a product of contact metamorphism of slates.

6. The writer believes that the granophyre was, with the adinole, formed by hydrothermal action at the contact; it is an adinole which has crystallized from a state of aqueous fusion and hence with all the textures of an igneous rock.

7. The literature of albite-rich igneous rocks shows their general association with gabbros, intrusive into argillites, and leads the writer to believe that a somewhat similar action may be of rather common occurrence.

In conclusion the writer desires to thank the Ontario Bureau of Mines for those chemical determinations of this paper which were made by Mr. N. L. Turner, provincial assayer.

Editorial

The Northern Mewuk say: "In the beginning the world was rock. Every year the rains came and fell on the rock and washed off a little; this made earth. By and by plants grew on the earth and their leaves fell and made more earth. Then pine trees grew and their needles and cones fell every year and with the other leaves and bark made more earth and covered more of the rock.

"If you look close at the ground in the woods you will see how the top is leaves and bark and pine needles and cones, and how a little below the top these are matted together, and a little deeper are rotting and breaking up into earth. This is the way the world grew—and is growing still."

This fragment of dynamic geology is taken from C. Hart Merriam's *The Dawn of the World*, a book recording the lore, chiefly mythic, of the Mewan Indians of California. The Northern Mewuk live on the western slope of the Sierra Nevada, a region well calculated to exhibit the relations of regolith and soil to bed rock and to vegetation.

G. K. G.

Reviews

The Geology and Ore Deposits of Goldfield, Nevada. By Frederick Leslie Ransome, assisted in the field by W. H. Emmons and G. H. Garrey. U.S. Geol. Surv. Professional Paper 66.

Aside from the importance of a careful and thorough description of a region so rich in mineral deposits as that of Goldfield, the present volume is especially interesting to students of economic geology in that it describes a practically new type of wall-rock alteration. Hitherto the primary deposition of deposits of gold, silver, and copper have been generally ascribed to the agency of hot ascending alkaline solutions; the minerals associated with the ores at Goldfield show, however, that the waters at the time of deposition were highly acid in character. To this type of deposition the name "alunitic and kaolinitic gold-quartz veins" is applied.

The geology of the district is comparatively simple: a basement complex of metamorphic rocks, intruded by masses of alaskite, probably in early Cretaceous, and overlain by a succession of Tertiary lava-flows and lake-beds. Of the lava-flows there are six rhyolites, a latite, three andesites, four dacites, and two basalts. The lake-beds are probably Miocene. All of these rocks have received a careful petrographical description.

Some ore-deposits occur in andesite, but most of them are in dacite. They are complex mineralogically, occurring in irregular tabular deposits which are approximately defined by the term metasomatic fissure veins. The most notable features of the ore-bodies are their remarkable richness and their equally remarkable irregularity. Three distinct types of wall-rock alteration are recorded; the first results in craggy outcrops of silicified volcanic rock, which form a marked feature of the topography; the second is a soft, light-colored mass of quartz, alunite, kaolinite, and pyrite; the third type is propylitic with the formation of calcite, epidote, chlorite, and pyrite. The ores are closely associated with the first two types of alteration, though the alteration is much more extensive than the ore deposits. It is the extensive formation of sulphate minerals, alunite, and kaolinite, in close association with primary ores, that gives to the deposits their chief genetic interest. The changes in the dacite have been carefully studied both qualitatively and quantitatively, as this method probably furnishes the best clue to the nature of the depositing solutions. The

theory reached by the authors is that of simultaneous solfatarism and oxidation. It is supposed that the ascending waters carried, besides the heavy metals, hydrogen sulphide, carbon dioxide, and alkalies. The hydrogen sulphide was oxidized near the surface to sulphuric acid, which, descending, met more of the uprising currents and caused the deposition of the ores.

The age of the ore deposits is placed in the late Pliocene, and it is thought that they were formed at a depth of not more than 1,000 feet.

E. R. L.

The Vertebrata of the Oligocene of the Cypress Hills, Saskatchewan. By LAWRENCE M. LAMBE. Contributions to Canadian Paleontology, Vol. III, Part IV. Canada Department of Mines, Geological Survey Branch. 64 pages of text and 7 plates.

The Oligocene of the district, composed chiefly of conglomerate, forms the capping of an extensive area of uplands, and lies unconformably on the Laramie. The vertebrate fauna, which has been known from these beds since 1883, has been correlated with the Titanotherium beds at Pipestone Springs, Montana. The publication of the present paper raises the number of species known from these deposits from 25 to over 50. Of these, seven species are of fishes, seven of reptiles, and the remainder of mammals; of the mammals two-thirds of the species belong to the Ungulata.

E. R. L.

Report on Tertiary Plants of British Columbia Collected by Lawrence G. Lambe in 1906, together with a Discussion of Previously Recorded Tertiary Floras. By D. P. PENHALLOW, Canada Department of Mines, Geological Survey Branch.

The report presents a very full account of the distribution and stratigraphic significance of the Tertiary floras of British Columbia. The localities are described at which Tertiary plants have been found, with lists of fossils from each locality; then the individual species are discussed briefly, with mention of the localities in which they are found; and following this is a discussion of the evidence of the floras of the several localities with regard to the age of the deposits and their relationship to similar deposits in other regions. The entire Tertiary flora falls into two groups belonging to the Eocene and the Oligocene periods. The report is rather poorly illustrated by a few text figures.

E. R. L.

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